DYNAMIC RESPONSE OF CYLINDRICAL SHELLS TO IMPULSIVE LOADING

James Walter Dumas

DYNAMIC RESPONSE OF CYLINDRICAL SHELLS TO IMPULSIVE LOADING

by

JAMES WALTER DUMAS

B.E.E., AUBURN UNIVERSITY

(1964)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF NAVAL ENGINEER

AND THE DEGREE OF

MASTER OF SCIENCE IN NAVAL ARCHITECTURE

AND MARINE ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF

TECHNOLOGY

JUNE, 1970

DYNAMIC RESPONSE OF CYLINDRICAL SHELLS TO IMPULSIVE LOADING

by

JAMES WALTER DUMAS

Submitted to the Department of Naval Architecture and Marine Engineering on May 21, 1970, in partial fulfillment of the requirement for the degree of Naval Engineer and the degree of Master of Science in Naval Architecture and Marine Engineering.

ABSTRACT

A program was undertaken to investigate the dynamic response of cylindrical shell panels to impulsive loads. Hot-rolled mild steel and aluminum 6061-T6 panels of various thicknesses and two panel sector sizes were loaded internally with DuPont "Detasheet" explosive. Calibration tests were conducted to determine the specific impulse of the explosive. The explosive impulse was sufficiently high to result in permanent plastic deformation of the shell panels. The final permanent deflections of the panel specimens were measured. Plots were made of the center deflection of the specimen as a function of the initial velocity and of the center deflection as a function of a nondimensional impulse parameter. Comparison of the results of tests on specimens made from mild steel, a strain-rate sensitive material, to those of aluminum 6061-T6, which is insensitive to strain-rate, revealed that the permanent deflections of the mild steel specimens were reduced. Thus it is concluded that the effect of material strain-rate sensitivity is important and must be considered in analyzing the response of cylindrical shells to impulsive loads. It is also concluded that the influence of geometry changes is insignificant on the cylindrical shell deflections in these tests.

Although, to the author's knowledge, there are no present theoretical methods of analysis with which these results may be compared, rigid-plastic methods of analysis are being developed at the Massachusetts Institute of Technology. It is hoped that the results reported here will aid in assessing these methods of analysis.

Thesis Supervisor: Norman Jones

Title: Associate Professor of Naval Architecture

ACKNOWLEDGEMENTS

The author owes a special debt of gratitude to Professor Norman Jones, his thesis supervisor, without whose support, advice, and encouragement, this report would not have been done. The author wishes to thank the Naval Ship Systems Command for additional financial support and Cdr. S. C. Reed for his assistance in obtaining it. The author wishes to take this opportunity to express his appreciation to Dr. J. W. Leech and O. E. Wallin of the Aeroelastic Laboratory for their kind cooperation and helpful assistance, and to Professor E. A. Witmer for permission to use the blast chamber for the explosive tests. Thanks go to Mr. George Falla of the Instrumentation Laboratory for operating the photographic equipment during the calibration tests. A special thanks goes to Patti, the author's wife, for her patience and encouragement, and for typing the report.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

H_e	thickness of sheet explosive
H_s	thickness of specimen
I	total impulse
I_o	specific impulse
L	semi-length of cylindrical panel
M_s	mass of specimen
V_n	average velocity of calibration specimen during h_n inches of travel
V_o	initial velocity of specimen
W_e	weight of explosive
a	radius of disc
d	mean diameter of cylindrical panel
e	elongation
h_n	distance of calibration specimen travel from inital position
n	integer (1, 2, 3....)
r	radial direction in polor coordinate system
t_n	time for calibration specimen to travel h_n inches
x,y	coordinates defined in Figures 2, 6a and 6b
δ	radial deflection of specimen
δ_m	maximum permanent radial deflection of specimen
δ_o	permanent radial reflection at center of specimen
θ	circumferential direction in polar coordinates
λ	impulse parameter $\rho \dfrac{V_o^2 d^2}{\sigma_o H_s^2}$

NOMENCLATURE (continued)

ν	kinematic viscosity
ρ	mass density
σ_o	yield stress of specimen material in simple tension
σ_u	ultimate tensile stress of specimen material
θ	circumferential length of cylindrical panel
ϕ_x, ϕ_y	rotation of calibration specimen about x-axis, y-axis

INTRODUCTION

Interest in the analysis and prediction of dynamic and permanent plastic deformations of structures has increased greatly during the past two decades. A wide range of materials in increasingly complex structural shapes are often required to perform under conditions which challenge the limits of mechanical strength and endurance of the structure. For example, in explosive forming of material into structural shapes, it may be necessary to predict the maximum energy which the material can absorb before failing. Or predictions of damage to structures which are involved in collisions with other bodies or subjected to explosive blasts may be of interest.

Analytical studies of plastic behavior of structures have been greatly simplified by the assumption that the material is rigid, perfectly plastic. This so-called rigid-plastic method of analysis has been shown by experiments to be generally valid under static loading conditions. Also, Symonds (1) indicated that the rigid-plastic analysis results in reasonable predictions of behavior of structures under dynamic loads when the external dynamic energy imparted to the structure is at least ten times the amount of energy which could be absorbed by the structure elastically and when the duration of the loading is short compared to the natural period of the structure.

Hodge (2, 3) investigated the response of a rigid, perfectly plastic cylindrical shell which is reinforced period-

ically along its axis with circumferential ring stiffeners and subjected to uniform radial dynamic pressures. The rigid-plastic approach was used with further assumption that strain-rate sensitivity of the material and geometry changes that might occur during deformation may be neglected. Other theoretical analyses of cylindrical shells subjected to various boundary conditions and types of dynamic loads invoked these same assumptions (4, 5, 6, 7 etc.). Jones (8) included the influence of changes in geometry in his theoretical analysis of cylindrical shells and concluded that "...geometry changes influence markedly the shell behavior even for quite small deflections and, therefore, they should be retained in any dynamic analyses of cylindrical shells with axial restraints".

Several experimental investigations have indicated that strain-rate sensitivity and finite-deflections influence the plastic behavior of such structures as beams, cantilevers, and plates subjected to impulsive loads (9-14). Florence (15) investigated the buckling phenomenon in cylindrical shells, and a similar experimental investigation of buckling of cylindrical panels was undertaken at Picatinny Arsenal (16). As for as the author is aware, no experimental or theoretical studies on cylindrical shell panels subjected to internally applied impulsive loads have been published.

This experimental study presents the results of tests on circular cylindrical panels which were subjected to internally applied uniformly distributed impulsive velocities

with sufficient initial energy to cause plastic deformation of the panel. The panels were clamped on all four edges or on two edges only, and were made of either mild steel or aluminum 6061-T6. Since mild steel is very sensitive to strain-rate and aluminum 6061-T6 is strain-rate insensitive, a comparision of the results allows the influence of strain-rate sensitivity to be estimated. The influence of finite-deflections is indicated by a non-linear deflection vs. impulse plot of the results.

It is hoped that these results may aid in assessing such numerical procedures as that devised by Leech, Witmer, and Pian (17) and in developing approximate rigid-plastic methods of analysis such as the present investigations in this area being undertaken in the Department of Naval Architecture and Marine Engineering at Massachusetts Institute of Technology.

EXPERIMENTAL DETAILS

DuPont "Detasheet" explosive in a range of thicknesses from .010-inches to .045-inches was applied to the surface of cylindrical shell panels. The panels were of two sizes, approximately 180-degrees and 90-degrees in circumference. All cylindrical panels were approximately 6-inches long and 4-inches in outside diameter. The explosive intensity was sufficient to cause measurable permanent plastic deformation of the specimens.

The majority of cylindrical shell specimens were 90-degree panels. These specimens were of two nominal thicknesses, .08-inches and .12-inches, and two materials, hot-rolled mild steel and aluminum 6061-T6. They were formed from plate stock in a rolling machine to the 4-inch diameter. The 2-inch flanges (for clamping) were formed in a brake press. The steel specimens were annealed and the aluminum specimens were heat treated to the T6 condition after the forming process. The specimen surfaces were cleaned with a wire wheel and a fine emory cloth. Variation in thickness was found to be less than $\pm$.0003-inch. Figure 1 illustrates the 90-degree specimen in its clamps. The clamps were made of ½-inch thick steel plate. They were serrated and case-hardened in an attempt to ensure that fully clamped support condition, with no slippage of the specimen, would exist.

The 180-degree specimens were cut and milled in the ma-

chine shop from commercially available steel and aluminum tubing. The hot-rolled steel was welded tubing. The weld was not included in the specimen. The aluminum 6061-T6 specimens were milled from .226-inch thickness, 4-inch outside diameter pipe. The specimen surfaces were left in the milled finish. The clamps were made from cold-rolled 1018 steel seamless tubing. They were also serrated and case-hardened. Either all four edges or two edges were clamped. Figures 2a and 2b illustrate the 180-degree specimen in its clamps.

The 180-degree specimens were loaded with "Detasheet" explosive over the entire inner surface for most tests. Three 180-degree mild steel specimens were loaded externally with Detasheet over an area 3-in x 4-in on the geometric center of the specimen's outer surface. These three tests were conducted to examine the response to an external load of the 180-degree, 2-edges-clamped specimen and its clamp apparatus.

The 90-degree panels were loaded over a 2-in x 3-in rectangular area of the center of the inner surface.

A ½-inch layer of low density (.027 g/cm^3) polyeurethene foam was employed as an attenuator between the sheet explosive and the specimen surface. This explosive-attenuator system was calibrated and found to have a specific impulse of 17.69 x 10^4 dyne sec/g or 0.3977 lb sec/g (see Appendix A). It was only necessary to weigh the explosive to compute the actual impulse imparted to the specimen in

each test. DuPont 4684 cement was used between the "Detasheet", foam, and the specimen.

The specimen-clamps arrangement (Figure 1 or Figures 2a and 2b) was bolted to the metal support table (Figure 3). The table was constructed of ½-inch steel plate and 6-in x 4-in I-beams. It was used for supporting specimens in all tests, including the impulse calibration tests. Figures 4a and 4b illustrate the general arrangement of apparatus for the tests. A "Detasheet" leader .125-in x .010--in x 20-in was employed between the explosive sheet and a No. 6 electric blasting cap. The leader was attached to the geometric center of the explosive sheet on the specimen. In some cases, the leader was split, with the two ends attached to the explosive sheet symmetrically about its center. The most effective method of attaching the leader was simply pressing the end of the leader into the sheet with a finger. The split leader was used so that the effect of the leader on the specimen deflection could be observed.

The deflections were measured to the nearest 0.001-in. or 0.0001-in. by dial gauges arranged as in Figure 5. The measurements were taken prior to deformation and after deformation with the specimen in its clamps. This procedure assured that any strain put on the specimen by the clamps would not affect the deflection measurements. The final deflection was measured at points in a grid 15-degrees circumferentially by 1-inch axially as illustrated in Figures 6a and 6b.

The average density of each material was obtained by carefully weighing several samples and measuring their volume using a water displacement method. The density of mild steel was found to be 7.26×10^{-4} lb sec $^2/in^4$. The 180-degree specimen aluminum had a density of 2.53×10^{-4} lb sec $^2/in^4$ while the 90-degree specimen aluminum material had a density of 2.51×10^{-4} lb sec $^2/in^4$.

Appendix D presents the results of tensile tests conducted on the specimen materials.

The average density of each material was found by carefully weighing several samples and measuring their volume using a water displacement method. The density of mild steel was found to be 7.33×10^{-4} lb sec $^2/in^4$. The 10-degree specimen aluminum had a density of 2.53×10^{-4} lb sec $^2/in^4$ while the 30-degree specimen aluminum material had a density of 2.51×10^{-4} lb sec $^2/in^4$.

Appendix C presents the results of tensile tests conducted on the specimen materials.

DISCUSSION OF RESULTS

The experimental data resulting from impulsively loaded cylindrical shell panels of aluminum 6061-T6 and hot-rolled mild steel are summarized in Tables 1a, 1b, 2a, and 2b.

The experimental values of permanent deflections of the two-edges-clamped 90-degree cylindrical panels resulting from uniformly distributed impulsive velocities (V_o), are presented for the aluminum 6061-T6 specimens and the mild steel specimens in Figure 13 and Figure 14, respectively. The maximum deflection occured at the center of the cylindrical panel in most cases, as expected; therefore, the center point deflection, δ_o, was used in all cases for consistency. It is seen that δ_o is related linearly to the inital velocity for a particular specimen thickness over the range of velocities examined in these tests. It is noted also that the relation must become nonlinear at velocities lower than those examined here, since if the straight lines are extended, they do not pass through the origins in the plots. Similar results have been found for fully clamped rectangular plates under impulsive loads (14).

The permanent deflections are tabulated for each specimen tested in Tables 3, 4a, and 4b. Typical permanent deflection profiles of the aluminum 6061-T6 and the mild steel cylindrical panels are shown in Figures 15a to 15f. Since the profiles are nearly symmetrical in each case, only half

profiles are plotted. It is noted that the profiles of the four-edges-clamped mild steel 180-degree panels (Table 4a (a-c) and Figure 15e) reveal the unusual characteristic that the minimum deflection occurred at the center of the panel. This was not expected and can possibly be due to relatively large slipping of the panels in the clamps. The 180-degree specimens experienced slippage in all cases ranging from approximately 1/64-inch to 1/16-inch. The same clamps were used in three tests of externally loaded specimens, and slippage was not observed in these tests. Data from the externally loaded specimens are tabulated in Table 4b. A typical profile is shown in Figure 15f. The 90-degree specimens showed no evidence of slipping in any of the tests.

The deflection parameter (δ_0/H_s) is plotted as a function of the impulse parameter (λ) for the 90-degree mild steel and aluminum 6061-T6 cylindrical panels in Figure 16. It is evident from this figure that permanent deflections of panels made from mild steel are smaller than deflections of similar panels of aluminum 6061-T6. This difference in deflections is believed to be due largely to the influence of the strain-rate sensitivity of the materials. The mild steel is strain-rate sensitive while the aluminum 6061-T6 is relatively insensitive to strain-rate.

The permanent deflections of mild steel and aluminum 6061-T6 beams and plates subjected to impulsive loads have been shown in References (13) and (14) to be influenced by geometry changes. This influence is evidenced by a

nonlinear relation of deflection ratio (δ_o/H_s) to impulse parameter (λ) at relatively high values of λ. Figure 16 appears to show an approximately linear relation of these parameters over the range of examined here. It appears, therefore, that bending only theory may predict results which closely approximate the experimental results over a range of δ_o/H_s less than 2.0. It is expected that any influence of geometry changes on the deflection of impulsively loaded cylindrical shell panels would be less than that observed in plates and beams. It is recommended, however, that further tests for investigating the influence of geometry changes on cylindrical shell deflections be conducted at higher values of impulse which would result in defelctions greater than twice the corresponding thickness of the shells.

CONCLUSIONS

A series of experimental tests were conducted in which circular cylindrical shell panels of mild steel and aluminum 6061-T6 were subjected to impulsive velocities of sufficient intensity to produce permanent deformation of the panels. Approximately 30 tests were conducted on panels of various thicknesses and two panel sector sizes. Most panels were 90-degrees in circumference and clamped on two edges only.

It is shown that the permanent deflection is linearly related to the initial velocity of the cylindrical panel over the range of velocity examined. It appears that this relation would be nonlinear at velocities lower than those used here, since extensions of the lines plotted do not pass through the origin.

It is evident that the mild steel specimen permanent deflections are less than those of geometrically similar aluminum 6061-T6 cylindrical panels subjected to the same magnitudes of impulse. It is concluded that this effect is due to the different material strain-rate sensitivities of the two materials tested.

Geometry changes appear not to influence the permanent deflections of the cylindrical shell panels tested. Thus, it is concluded that finite deflections may be disregarded in a rigid-plastic analysis of the response of cylindrical shell panels to impulsive loading when δ_0/H_s is less than approximately 2.0. It is recommended that the range of impulse be extended beyond that examined here in further tests to

determine the influence of geometry changes for deflection ratios greater than 2.0.

determine the influence of geometry changes for reduction
ratios greater than 2.0.

TABLE 1a

DATA FOR ALUMINUM 6061-T6 SPECIMENS

Spec No.	θ deg	θ in	H_s in	2L in	M_s $\frac{\text{lb sec}^2}{\text{in}}$ $\times 10^{-4}$	ρ $\frac{\text{lb sec}^2}{\text{in}^4}$ $\times 10^{-4}$	d in
1	183.0	6.40	.1171	6.00	11.4	2.53	3.88
2	183.0	6.40	.1524	5.87	14.5	2.53	3.85
3	183.0	6.40	.1522	5.82	14.3	2.53	3.85
4	183.0	6.40	.1524	5.92	14.6	2.53	3.85
5	90.0	3.14	.1244	5.98	5.88	2.51	3.88
6	91.2	3.18	.1248	5.95	5.95	2.51	3.88
7	90.3	3.15	.1248	5.98	5.90	2.51	3.88
8	90.1	3.14	.1249	5.99	5.90	2.51	3.88
9	90.4	3.15	.1248	5.98	5.90	2.51	3.88
10	90.4	3.15	.0818	5.98	3.87	2.51	3.92
11	90.4	3.15	.0815	5.98	3.86	2.51	3.92
12	90.6	3.16	.0815	5.97	3.86	2.51	3.92
13	91.2	3.18	.0816	5.98	3.90	2.51	3.92
14	90.6	3.16	.0816	5.98	3.87	2.51	3.92

TABLE 1b

SUMMARY OF ALUMINUM 6061-T6

EXPERIMENTAL DATA

Spec No.	W_e g	H_e in	V_o in/sec	δ_m in	δ_o in	$\frac{\delta_o}{H_s}$	λ	Remarks
1	6.97	.010	2771.97	.0418	.0371	.317	60.09	1
2	7.35	.010	2015.86	.0510	.0468	.307	18.14	2
3	15.55	.020	4324.64	.1956	.1867	1.23	149.4	2
4	21.13	.030	5755.75					3
5	1.34	.010	906.32	.0212	.0212	.170	4.85	4
6	2.11	.015	1410.3	.0633	.0633	.507	11.68	4
7	2.64	.020	1779.5	.0995	.0995	.797	18.65	4,5
8	2.44	.020	1644.89	.0930	.0930	.745	15.88	4,6
9	3.64	.025	2453.41				32.2	4,7
10	1.35	.010	1387.31	.0652	.0637	.779	23.57	4,8
11	1.81	.015	1864.86	.1410	.1410	1.72	51.46	4,5,6
12	1.57	.015	1617.59	.1002	.0962	1.18	38.72	4,6,8
13	1.20	.010	1223.69	.0557	.0557	.683	22.09	4,6
14	1.67	.015	1716.17	.1107	.1068	1.31	43.43	4,5

REMARKS CODE FOR TABLE 1b

1	four edges clamped
2	specimen slipped in clamps
3	specimen torn out of clamps and split into five pieces due to excessive explosive
4	Detasheet covered 2-in x 3-in rectangular area of specimen center - two edges clamped
5	very slight shear of specimen at clamped edge
6	Detasheet perforated in symmetrical pattern for reduction of explosive impulse
7	specimen completely sheared at one clamped edge
8	leader split into at specimen and positioned symmetrically about center of Detasheet

TABLE 2a

DATA FOR HOT-ROLLED MILD STEEL SPECIMENS

Spec No.	θ deg	θ in	H_s in	2L in	M_s $\frac{\text{lb sec}^2}{\text{in}}$ x 10^{-4}	ρ $\frac{\text{lb sec}^2}{\text{in}^4}$ x 10^{-4}	d in
1	183.0	6.40	.1197	6.0	33.37	7.26	3.88
2	183.0	6.40	.1221	6.0	34.04	7.26	3.87
3	183.0	6.40	.1222	6.0	34.04	7.26	3.87
4	90.4	3.15	.1206	5.98	16.49	7.26	3.88
5	90.6	3.16	.1206	5.99	16.57	7.26	3.88
6	91.2	3.18	.1202	5.98	16.59	7.26	3.88
7	91.2	3.18	.1209	5.98	16.69	7.26	3.89
8	90.4	3.15	.1205	5.98	16.48	7.26	3.88
9	90.0	3.14	.0757	5.97	10.30	7.26	3.92
10	90.6	3.16	.0764	5.98	10.48	7.26	3.92
11	91.2	3.18	.0760	5.96	10.46	7.26	3.92
12	90.4	3.15	.0755	5.98	10.33	7.26	3.92
13	90.4	3.15	.0759	5.98	10.38	7.26	3.92
14	183.0	6.40	.1608	5.90	44.08	7.26	3.84
15	183.0	6.40	.1610	5.90	44.14	7.26	3.84
16	183.0	6.40	.1610	5.90	44.14	7.26	3.84

TABLE 2b

SUMMARY OF HOT-ROLLED MILD STEEL

EXPERIMENTAL DATA

Spec No.	W_e g	H_e in	V_o in/sec	δ_m in	δ_o in	$\frac{\delta_o}{H_s}$	λ	Remarks
1	13.79	.020	1643.48	.0332	.0212	.1771	39.85	1
2	31.55	.045	3686.09	.1837	.0956	.7829	187.5	1,2
3	20.74	.030	2423.12	.0721	.0520	.4255	82.69	1,2
4	4.76	.030	1141.94	.0960	.0960	.763	26.56	3
5	6.27	.045	1504.88	.1722	.1703	1.41	46.03	3,4
6	3.37	.025	807.87	.0470	.0470	.391	13.38	3,5
7	5.02	.035	1196.20	.1020	.1020	.843	29.21	3
8	5.77	.040	1392.43	.1481	.1481	1.23	39.55	3,4
9	4.78	.030	1845.64					3,6
10	1.84	.015	698.25	.0273	.0273	.357	32.93	3,7
11	3.15	.025	1197.66	.1272	.1135	1.482	78.48	3,4
12	2.65	.020	1020.33	.0905	.0844	1.118	57.72	3,4,5
13	2.17	.015	831.41	.0480	.0480	.632	37.92	3
14	8.38	.030	756.60	.060	.056	.373	4.58	8
15	17.60	.060	1585.75	.494	.494	3.069	20.09	8
16	13.12	.045	1182.11	.1620	.1620	1.006	11.16	8

REMARKS CODE FOR TABLE 2b

1 four edges clamped

2 specimen slipped im clamps

3 Detasheet covered 2-in x 3-in rectangular area of specimen center - two edges clamped

4 very slight shear of specimen at clamped edge

5 leader split into at specimen and positioned symmetrically about center of Detasheet

6 specimen completely sheared at one clamped edge

7 Detasheet perforated in symmetrical pattern for reduction of explosive impulse

8 external load - two edges clamped - Detasheet covered 3-in x 4-in rectangular area of outside surface of specimen center

TABLE 3

PERMANENT DEFLECTION DATA

FOR ALUMINUM 6061-T6 SPECIMENS

(Deflection values are in inches. See Figures 6a and 6b for x, y coordinates.)

a. Aluminum 6061-T6 Specimen No. 1

x / y	1	2	3	4	5
1	.020	.025	.017	.019	.027
2	.0263	.0375	.0316	.0273	.0406
3	.022	.038	.039	.036	.046
4	.021	.0343	.0385	.0349	.0390
5	.020	.036	.037	.031	.041
6	.0249	.0345	.0371	.0313	.0407
7	.028	.034	.038	.035	.034
8	.032	.0411	.0418*	.0321	.0259
9	.029	.037	.041	.038	.037
10	.0343	.0404	.0406	.0365	.0402
11	.030	.041	.033	.034	.043

TABLE 3 (continued)

b. Aluminum 6061-T6 Specimen No. 2

x y	1	2	3	4	5
1	.01	.01	.01	.012	.014
2	.017	.017	.019	.020	.023
3	.0185	.0220	.0235	.0246	.0284
4	.036	.038	.038	.037	.038
5	.0424	.0467	.0468	.0493	.0449
6	.048	.050	.051*	.050	.048
7	.0493	.0479	.0478	.0491	.0500
8	.046	.046	.045	.048	.046
9	.0336	.0310	.0321	.0337	.0339
10	.024	.025	.025	.027	.026
11	.015	.015	.012	.012	.012

TABLE 3 (continued)

c. Aluminum 6061-T6 Specimen No. 3

x y	1	2	3	4	5
1	.083	.089	.098	.096	.085
2	.1149	.1247	.1271	.1236	.1162
3	.134	.136	.141	.138	.136
4	.1287	.1278	.1318	.1289	.1329
5	.179	.171	.176	.179	.179
6	.1949	.1729	.1869	.1888	.1956*
7	.181	.156	.174	.179	.187
8	.1464	.1244	.1413	.1435	.1419
9	.148	.136	.158	.146	.141
10	.1272	.1330	.1448	.1301	.1148
11	.083	.090	.098	.092	.076

TABLE 3 (continued)

d. Aluminum 6061-T6 Specimen No. 5

x y	1	2	3	4	5
1	.004	.013	.014	.010	.002
2	.0076	.0151	.0207	.0146	.0048
3	.0095	.0162	.0212*	.0152	.0070
4	.0056	.0137	.0178	.0121	.0043
5	.003	.011	.014	.009	.002

e. Aluminum 6061-T6 Specimen No. 6

x y	1	2	3	4	5
1	.005	.035	.044	.037	.009
2	.0088	.0347	.0565	.0441	.0103
3	.0098	.0396	.0633*	.0441	.0095
4	.0090	.0388	.0465	.0426	.0067
5	.003	.020	.028	.026	.003

TABLE 3 (continued)

f. Aluminum 6061-T6 Specimen No. 7

x	1	2	3	4	5
y					
1	.010	.052	.065	.050	.008
2	.0178	.0797	.0910	.0733	.0121
3	.0222	.0855	.0995*	.0777	.0153
4	.0173	.0833	.0978	.0785	.0136
5	.010	.050	.060	.049	.008

g. Aluminum 6061-T6 Specimen No. 8

x	1	2	3	4	5
y					
1	.009	.054	.070	.056	.012
2	.0014	.0673	.0894	.0636	.0227
3	.0167	.0682	.0930*	.0654	.0253
4	.0121	.0635	.0871	.0579	.0216
5	.011	.043	.054	.044	.009

TABLE 3 (continued)

h. Aluminum 6061-T6 Specimen No. 10

x / y	1	2	3	4	5
1	.006	.040	.049	.043	.011
2	.0118	.0562	.0638	.0534	.0140
3	.0133	.0472	.0637	.0470	.0137
4	.0116	.0492	.0652*	.0554	.0116
5	.010	.044	.057	.044	.004

i. Aluminum 6061-T6 Specimen No. 11

x / y	1	2	3	4	5
1	.024	.086	.106	.074	.014
2	.0338	.1190	.1307	.1067	.0184
3	.0356	.1208	.1410*	.1074	.0239
4	.0358	.1169	.1305	.1235	.0222
5	.013	.074	.115	.090	.010

TABLE 3 (continued)

j. Aluminum 6061-T6 Specimen No. 12

x y	1	2	3	4	5
1	.007	.050	.062	.048	.012
2	.0144	.0746	.0862	.0681	.0154
3	.0182	.0783	.0962	.0757	.0192
4	.0208	.0756	.1002*	.0754	.0194
5	.015	.068	.08	.058	.010

k. Aluminum 6061-T6 Specimen No. 13

x y	1	2	3	4	5
1	.003	.032	.037	.039	.015
2	.066	.0422	.0532	.0473	.015
3	.097	.0463	.0557*	.0489	.0146
4	.0109	.0448	.0504	.0357	.0090
5	.011	.028	.034	.033	.006

TABLE 3 (continued)

1. Aluminum 6061-T6 Specimen No. 14

x y	1	2	3	4	5
1	.012	.059	.076	.069	.019
2	.0157	.0888	.1107*	.0949	.0268
3	.0168	.0850	.1068	.0781	.0237
4	.0127	.0833	.1027	.0896	.0121
5	.010	.064	.077	.062	.003

* indicates maximum permanent deflection

TABLE 4a

PERMANENT DEFLECTION DATA FOR

MILD STEEL SPECIMENS

a. Mild Steel Specimen No. 1

x / y	1	2	3	4	5
1	.016	.017	.019	.020	.018
2	.0254	.0276	.0317	.0332*	.0314
3	.017	.018	.024	.021	.018
4	.0261	.0266	.0307	.0289	.0228
5	.024	.020	.024	.021	.018
6	.0235	.0190	.0212	.0193	.0173
7	.023	.022	.023	.021	.021
8	.0251	.0222	.0257	.0235	.0218
9	.016	.015	.016	.016	.017
10	.0235	.0228	.0252	.0233	.0224
11	.018	.017	.016	.017	.019

TABLE 4a (continued)

b. Mild Steel Specimen No. 2

x y	1	2	3	4	5
1	.098	.114	.107	.107	.096
2	.1500	.1663	.1694	.1681	.1498
3	.131	.140	.141	.141	.127
4	.1312	.1343	.1343	.1343	.1294
5	.115	.107	.100	.104	.112
6	.1143	.1031	.0956	.0979	.1077
7	.117	.106	.101	.105	.112
8	.1340	.1380	.1392	.1378	.1375
9	.138	.150	.151	.152	.140
10	.1618	.1800	.1837*	.1796	.1668
11	.124	.132	.133	.130	.129

TABLE 4a (continued)

c. Mild Steel Specimen No. 3

x / y	1	2	3	4	5
1	.052	.042	.044	.041	.041
2	.0659	.0631	.0578	.0564	.0565
3	.057	.052	.051	.046	.050
4	.0569	.0450	.0558	.0500	.0533
5	.053	.047	.048	.051	.052
6	.0521	.049	.0431	.0463	.0520
7	.055	.050	.052	.051	.056
8	.0642	.0651	.0581	.0649	.0630
9	.066	.065	.069	.064	.061
10	.0692	.0721*	.0713	.0713	.0657
11	.049	.047	.050	.048	.046

TABLE 4a (continued)

d. Mild Steel Specimen No. 4

x y	1	2	3	4	5
1	.016	.051	.054	.037	.016
2	.0423	.0895	.0918	.0742	.0345
3	.0516	.0897	.0960*	.0843	.0399
4	.0417	.0796	.0814	.0707	.0297
5	.014	.030	.037	.028	.010

e. Mild Steel Specimen No. 5

x y	1	2	3	4	5
1	.022	.090	.120	.091	.025
2	.0583	.1332	.1722*	.1421	.0596
3	.0677	.1508	.1703	.1371	.0680
4	.0543	.1368	.1622	.1358	.0543
5	.022	.067	.084	.060	.021

TABLE 4a (continued)

f. Mild Steel Specimen No. 6

y \ x	1	2	3	4	5
1	.010	.019	.023	.015	.008
2	.0244	.0398	.0335	.0324	.0190
3	.0307	.0405	.0470*	.0375	.0238
4	.0227	.0249	.0383	.0315	.0192
5	.009	.019	.022	.015	.007

g. Mild Steel Specimen No. 7

y \ x	1	2	3	4	5
1	.013	.044	.064	.054	.021
2	.0429	.0912	.1004	.0885	.0451
3	.0555	.0948	.1020*	.0956	.0517
4	.0421	.0753	.0974	.0743	.0390
5	.019	.040	.047	.030	.010

TABLE 4a (continued)

h. Mild Steel Specimen No. 8

x	1	2	3	4	5
y					
1	.015	.051	.059	.055	.022
2	.0529	.1210	.1389	.1116	.0548
3	.0700	.1291	.1481*	.1193	.0673
4	.0583	.1242	.1386	.1073	.0427
5	.029	.073	.082	.058	.021

i. Mild Steel Specimen No. 10

x	1	2	3	4	5
y					
1	.007	.011	.017	.011	.005
2	.0081	.0172	.0198	.0185	.0038
3	.0086	.0174	.0273*	.0190	.0057
4	.0077	.0235	.0271	.0225	.0050
5	.004	.016	.019	.011	.004

TABLE 4a (continued)

j. Mild Steel Specimens No. 11

x	1	2	3	4	5
y					
1	.004	.058	.115	.102	.024
2	.0110	.0998	.1272*	.1074	.0297
3	.0159	.0846	.1135	.0995	.0278
4	.0131	.0701	.0920	.0894	.0227
5	.022	.043	.051	.038	.012

k. Mild Steel Specimen No. 12

x	1	2	3	4	5
y					
1	.008	.023	.049	.036	.008
2	.0173	.0625	.0787	.0602	.0164
3	.0239	.0683	.0844	.0706	.0247
4	.0244	.0726	.0905*	.0818	.0261
5	.019	.058	.083	.065	.002

TABLE 4a (continued)

1. Mild Steel Specimen No. 13

x / y	1	2	3	4	5
1	.005	.014	.023	.022	.006
2	.0071	.0359	.0434	.0387	.0101
3	.0078	.0453	.0480*	.0448	.0115
4	.0068	.0305	.0346	.0267	.0080
5	.006	.013	.017	.012	.004

* indicates maximum permanent deflection

TABLE 4b

PERMANENT DEFLECTION DATA FOR MILD STEEL SPECIMENS UNDER EXTERNAL LOAD

(minus (-) denotes outward deflections)

Mild Steel Specimen No. 14

x y	1	2	3	4	5
1					
2	-.007	-.018	-.027	-.021	-.014
3	.000	-.005	-.003	-.007	.002
4	.015	.018	.028	.023	.021
5	.033	.044	.054	.048	.046
6	.040	.050	.060*	.056	.052
7	.036	.045	.055	.052	.045
8	.013	.018	.026	.022	.019
9	-.004	-.008	-.012	-.012	-.005
10	-.022	-.026	-.027	-.027	-.026
11					

TABLE 4b (continued)

Mild Steel Specimen No. 15

x / y	1	2	3	4	5
1					
2	-.092	-.104	-.110	-.108	-.092
3	.006	.013	.015	.015	.004
4	.138	.225	.206	235	.132
5	.244	.348	.384	.350	.233
6	.291	.393	.494*	.398	.276
7	.235	.363	.390	.355	.221
8	.125	.256	.216	.260	.113
9	-.025	-.015	-.012	-.012	-.028
10	-.140	-.159	-.166	-.159	-.137
11					

TABLE 4b (continued)

Mild Steel Specimen No. 16

x	1	2	3	4	5
y					
1					
2	-.071	-.081	-.082	-.078	-.064
3	-.026	-.032	-.033	-.029	-.022
4	.045	.065	.066	.063	.038
5	.103	.141	.141	.137	.098
6	.136	.160	.162*	.161	.121
7	.121	.152	.154	.150	.107
8	.062	.088	.092	.088	.060
9	.008	-.001	-.002	.001	.001
10	-.045	-.056	-.061	-.058	-.053
11					

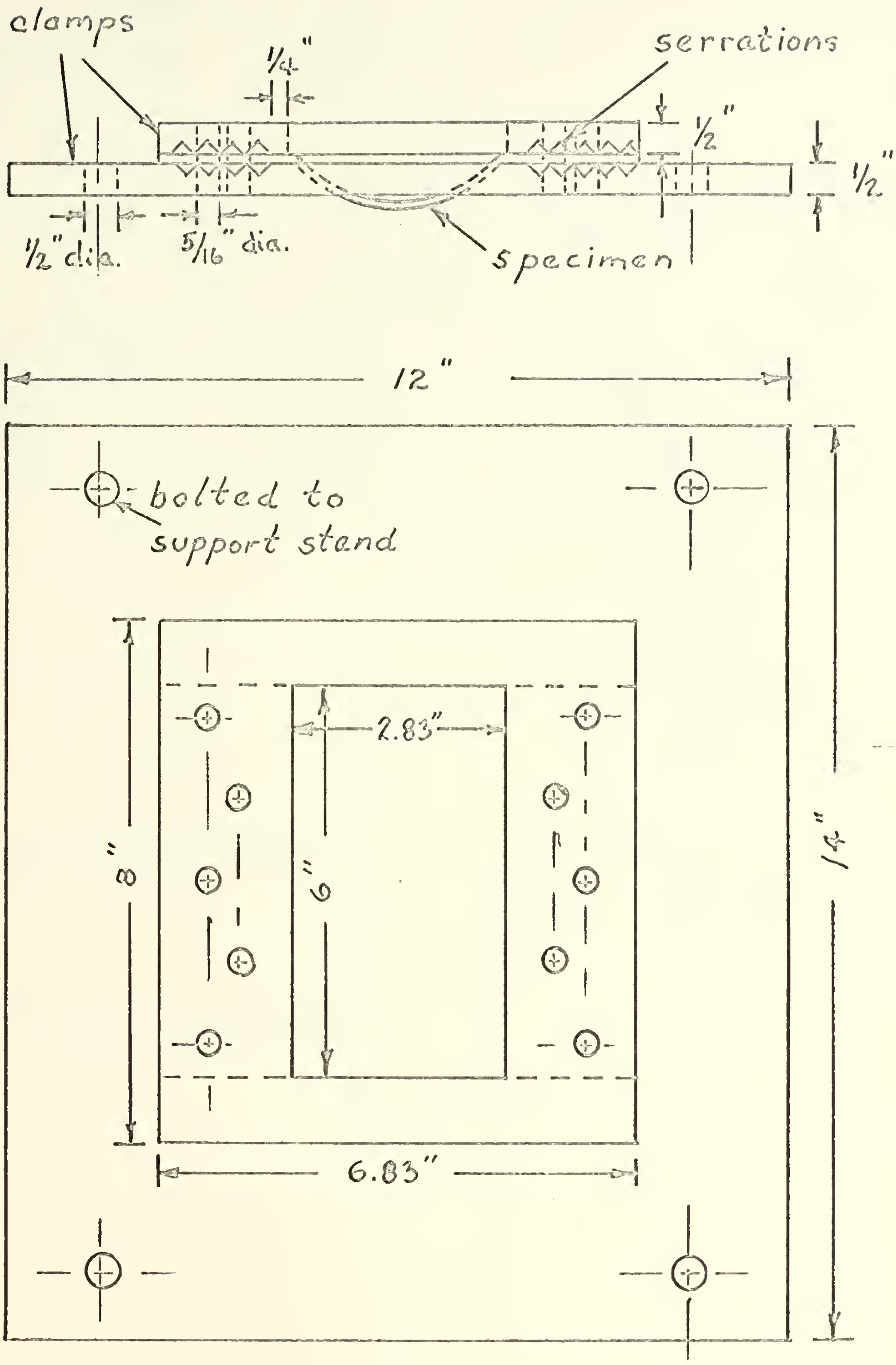


FIGURE 1   90 - Degree Specimen and Clamps

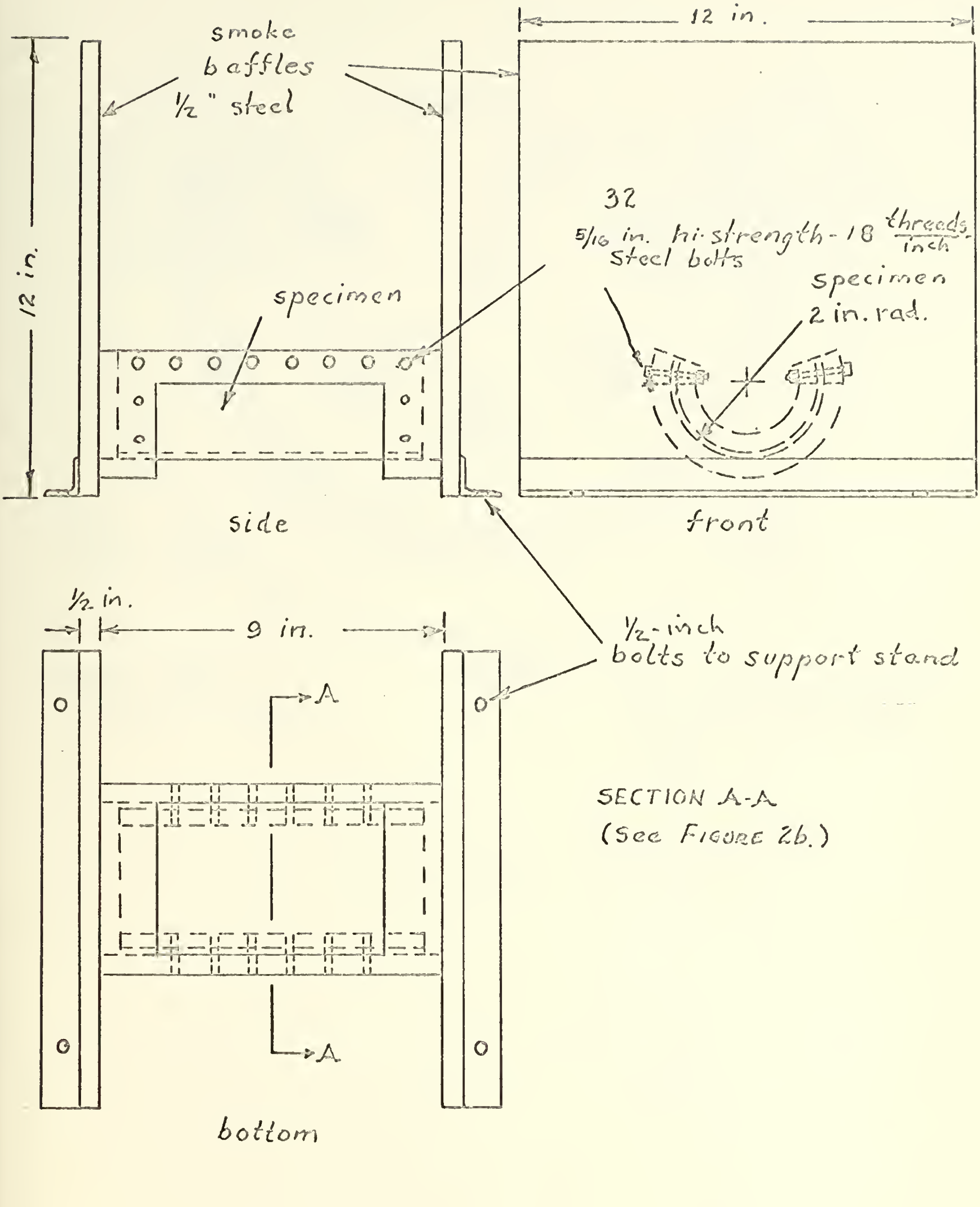
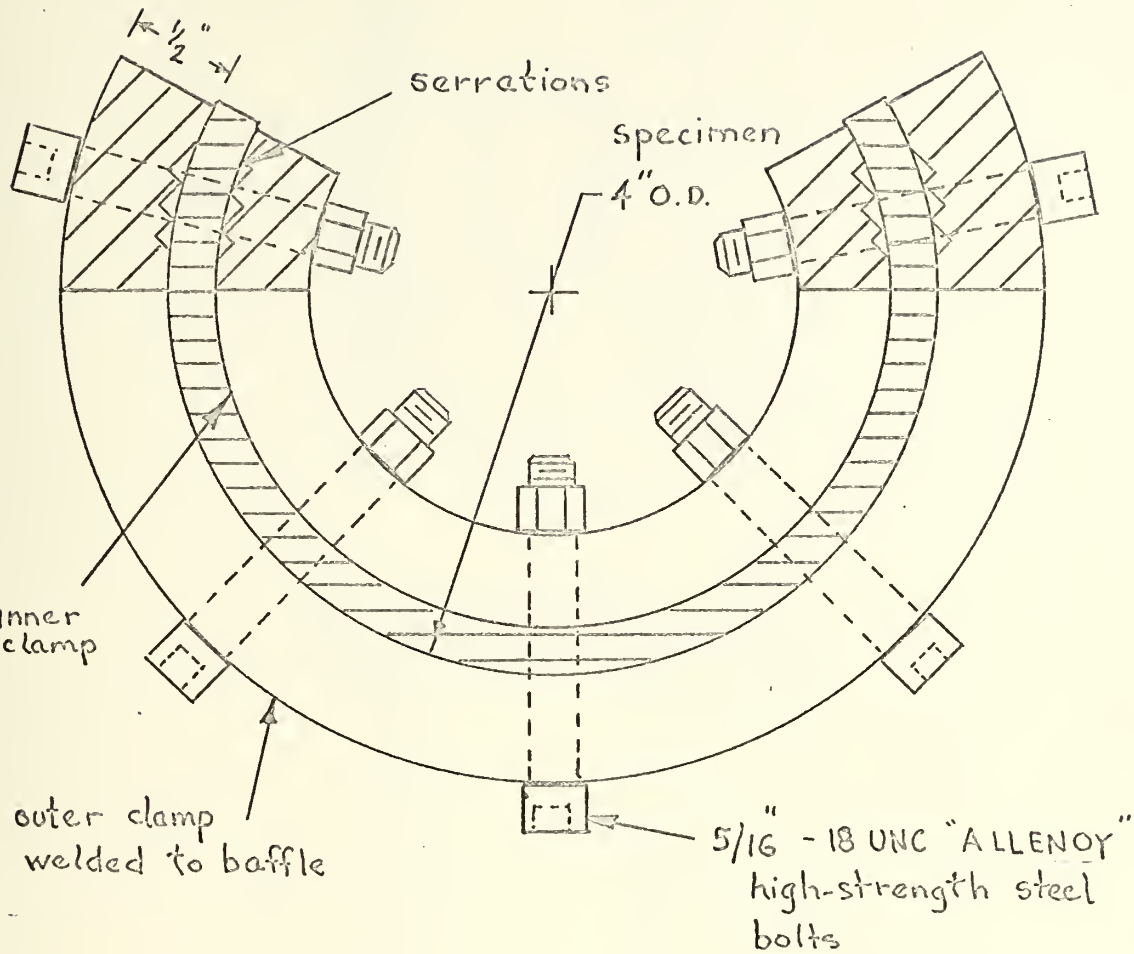


FIGURE 2a. 180-Degree Specimen and Clamps



SECTION A-A of FIGURE 2a.

FIGURE 2b 180 Degree Specimen in Clamps

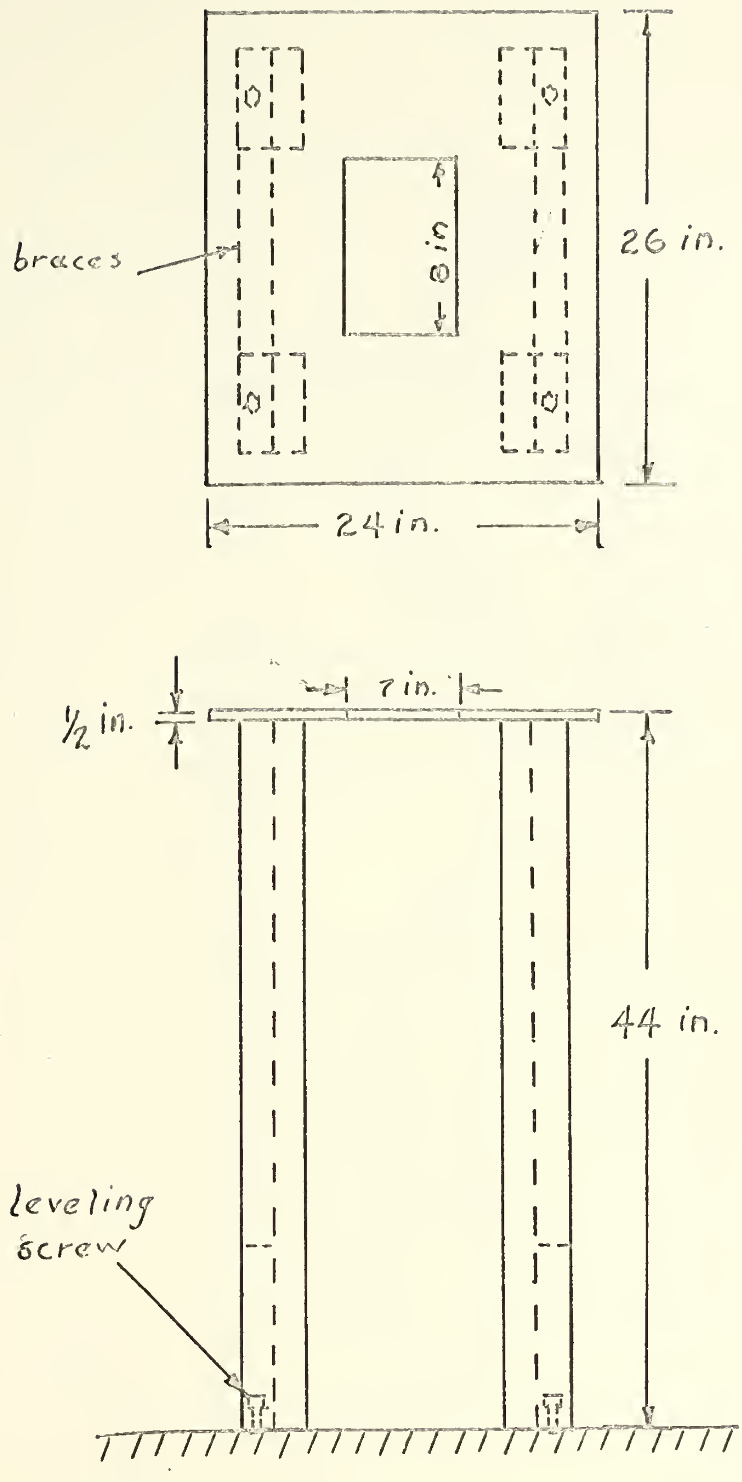


FIGURE 3 Support Stand

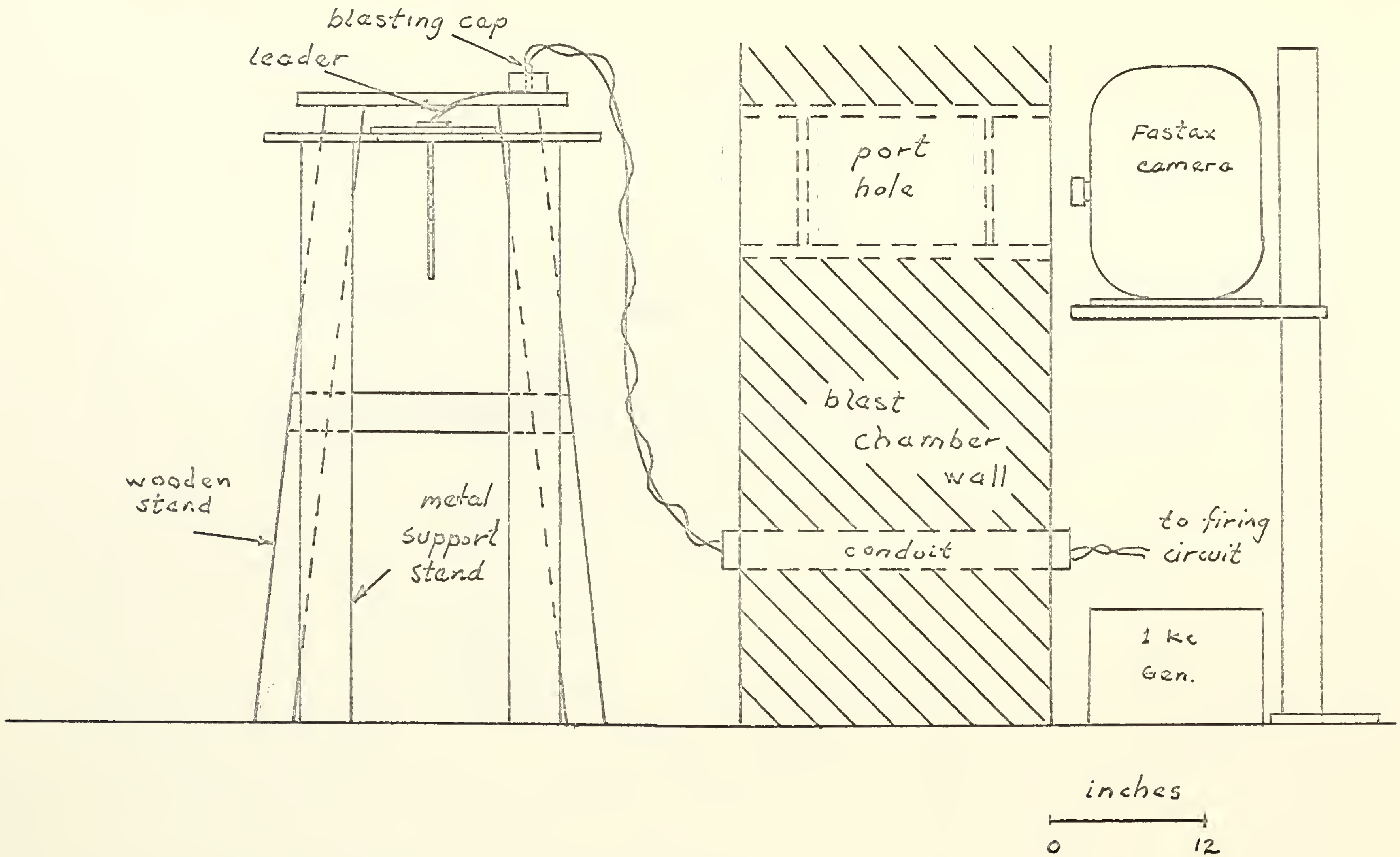


FIGURE 4a. Arrangement of Experimental Apparatus

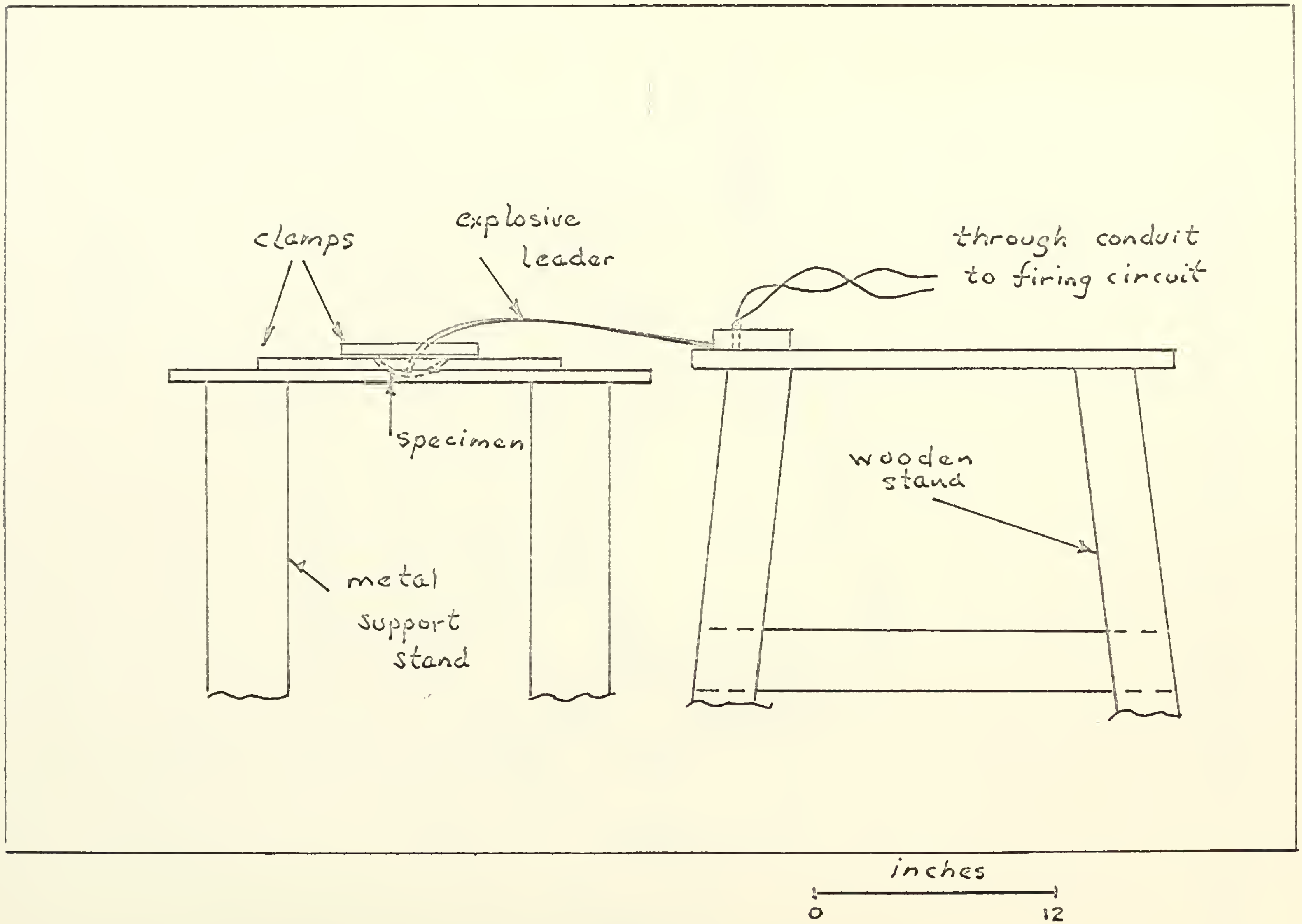


FIGURE 4b. Cylindrical Specimen Arrangement for Experiment

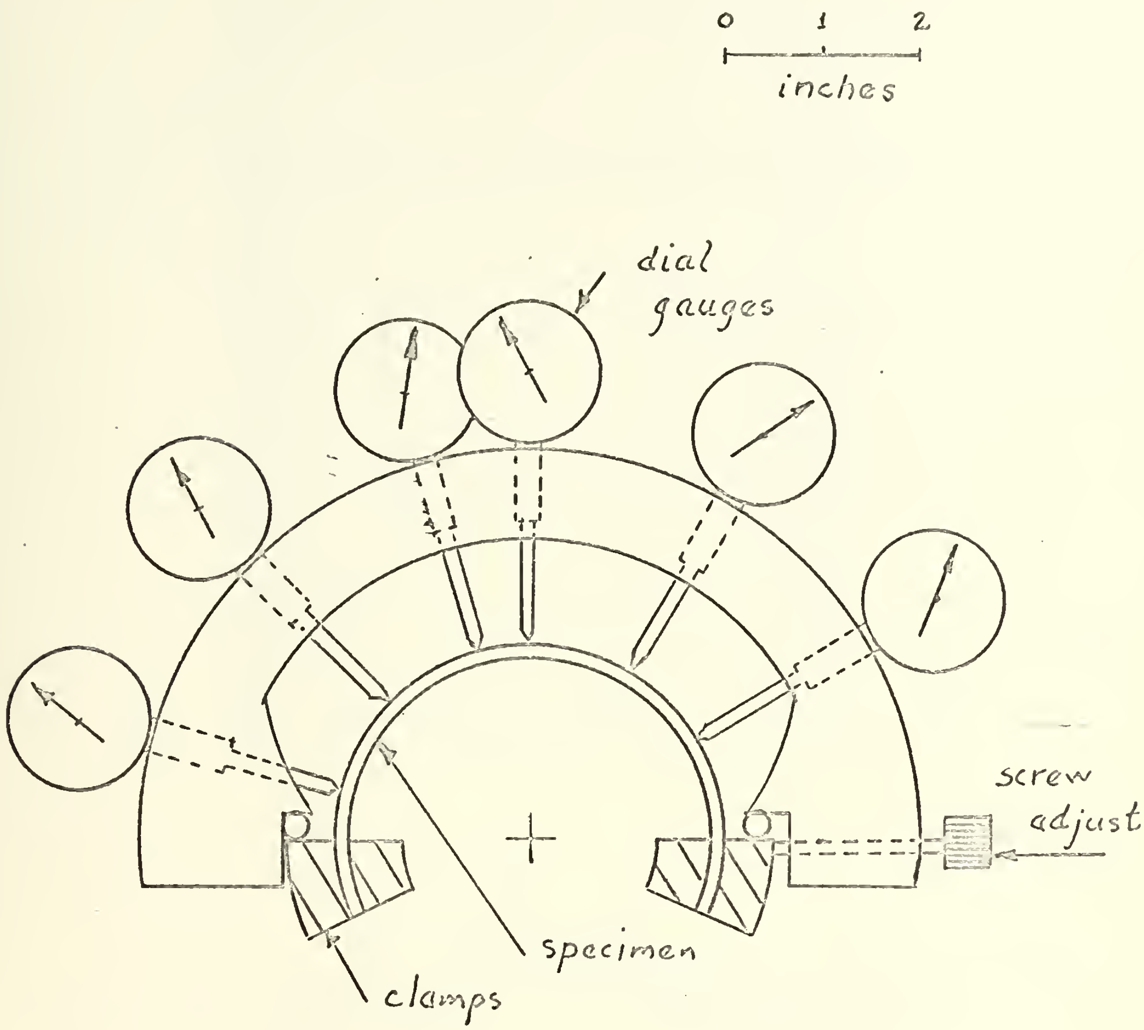


FIGURE 5 Apparatus for Measuring Deflection

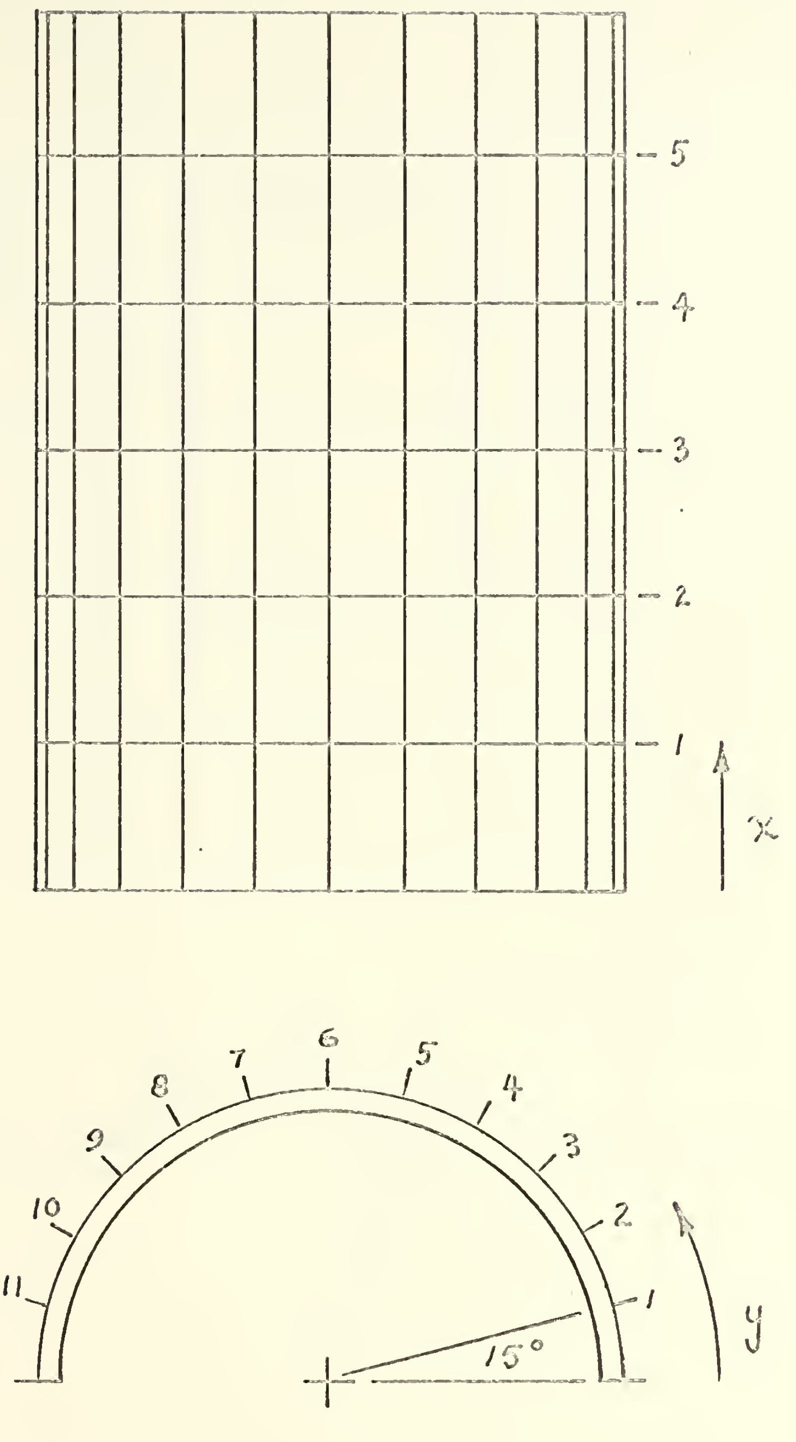


FIGURE 6a Specimen Grid Layout (180°)

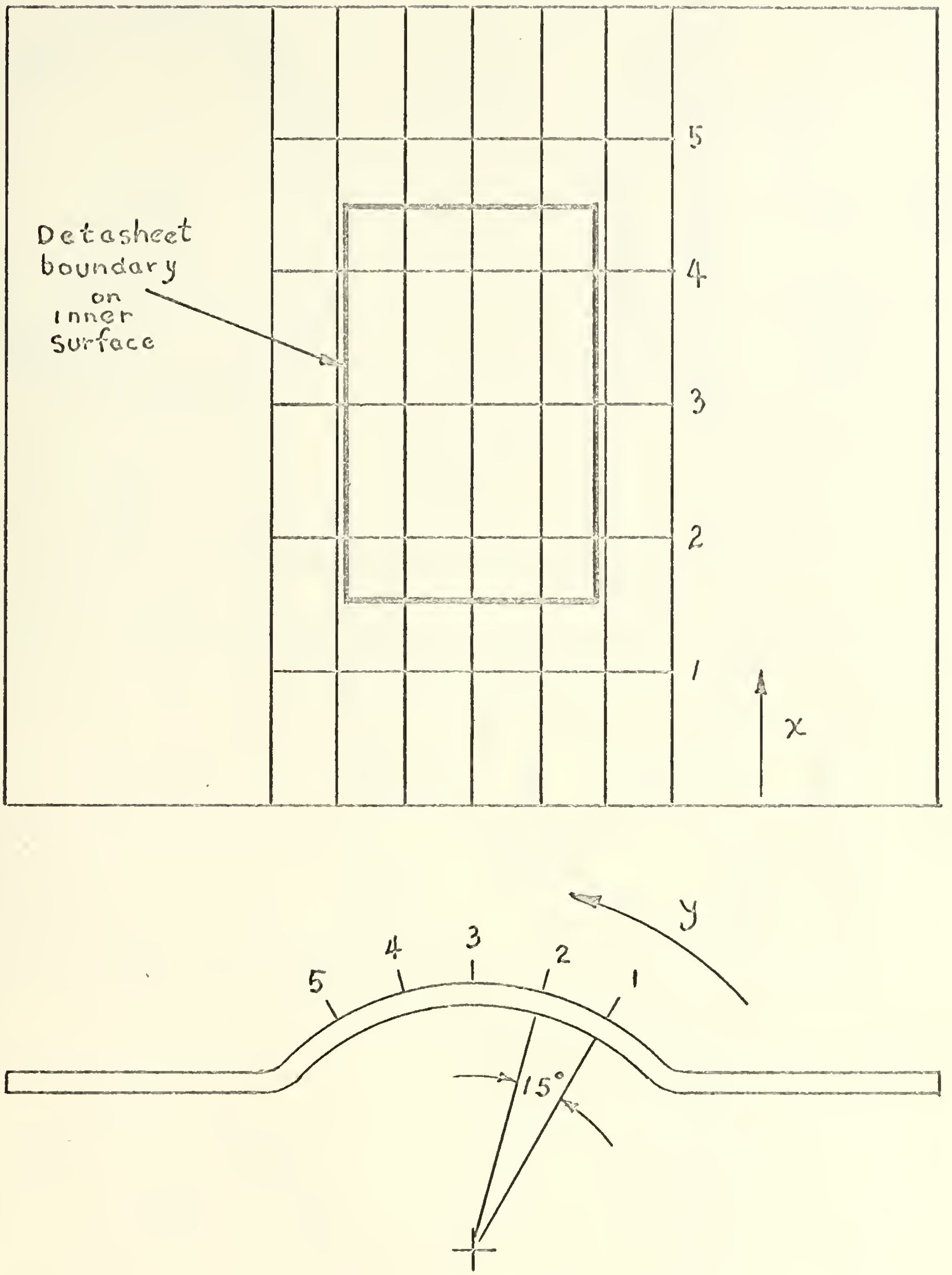


FIGURE 6b Specimen Grid Layout (90°)

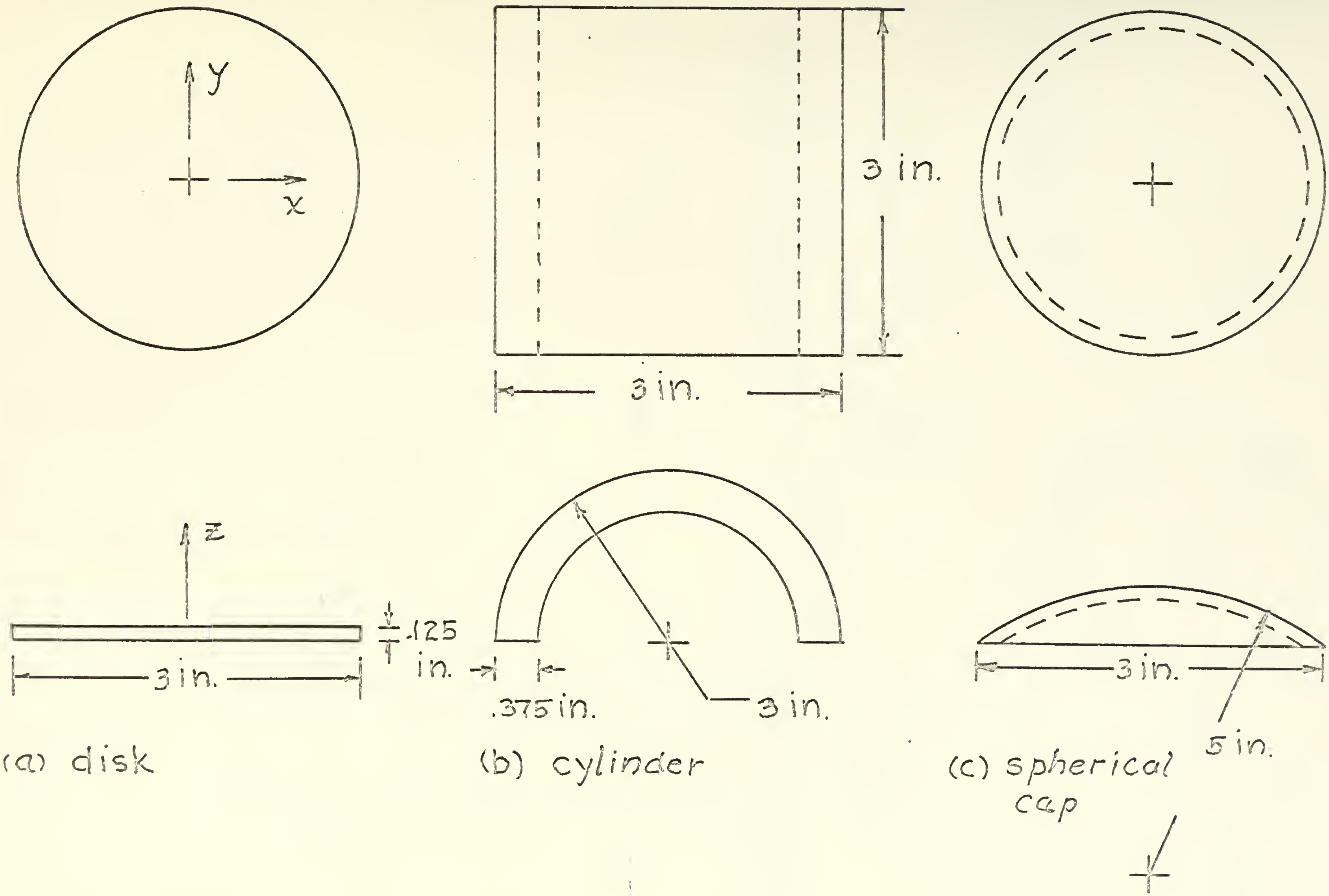


FIGURE 7 Calibration Specimens

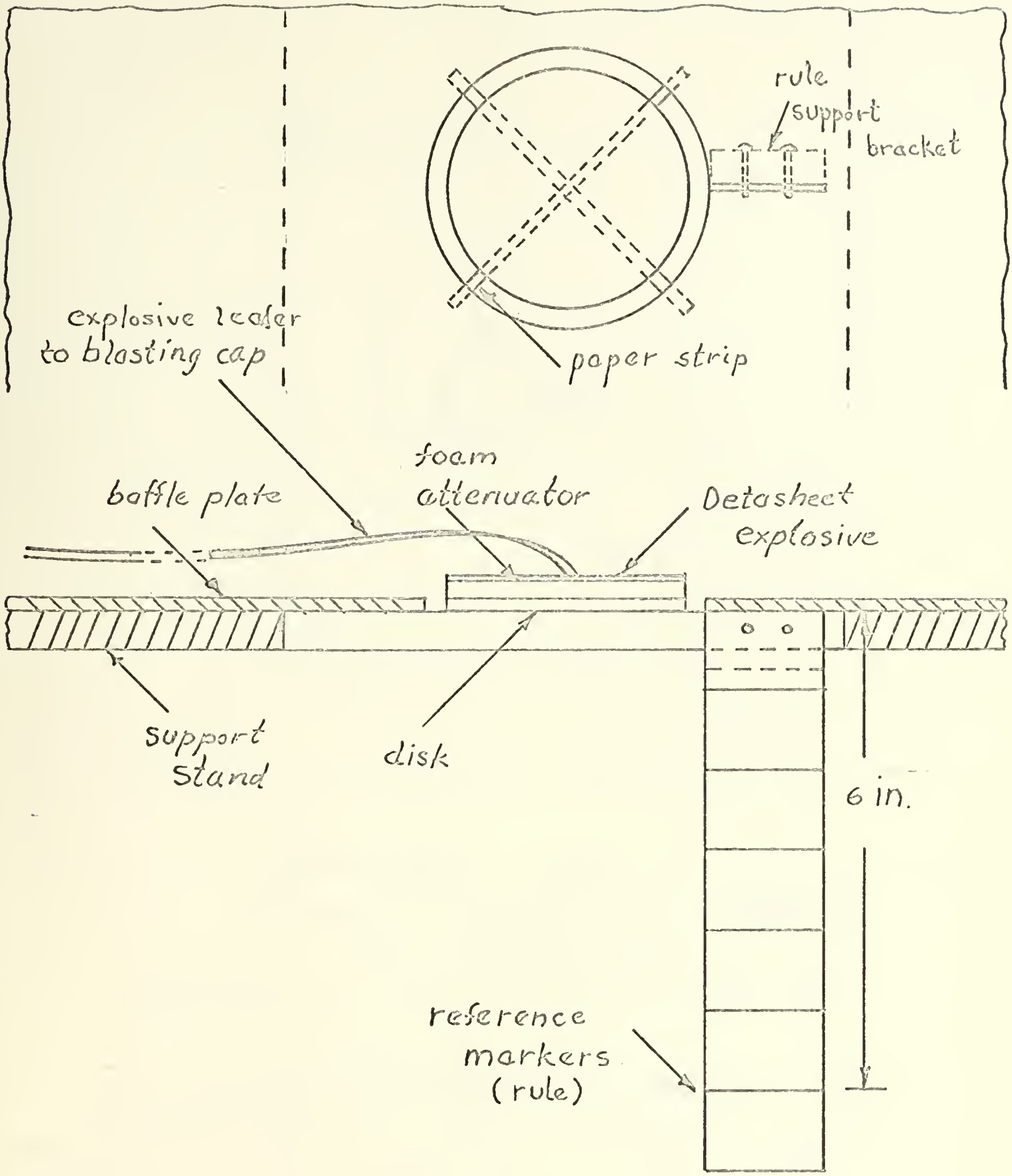
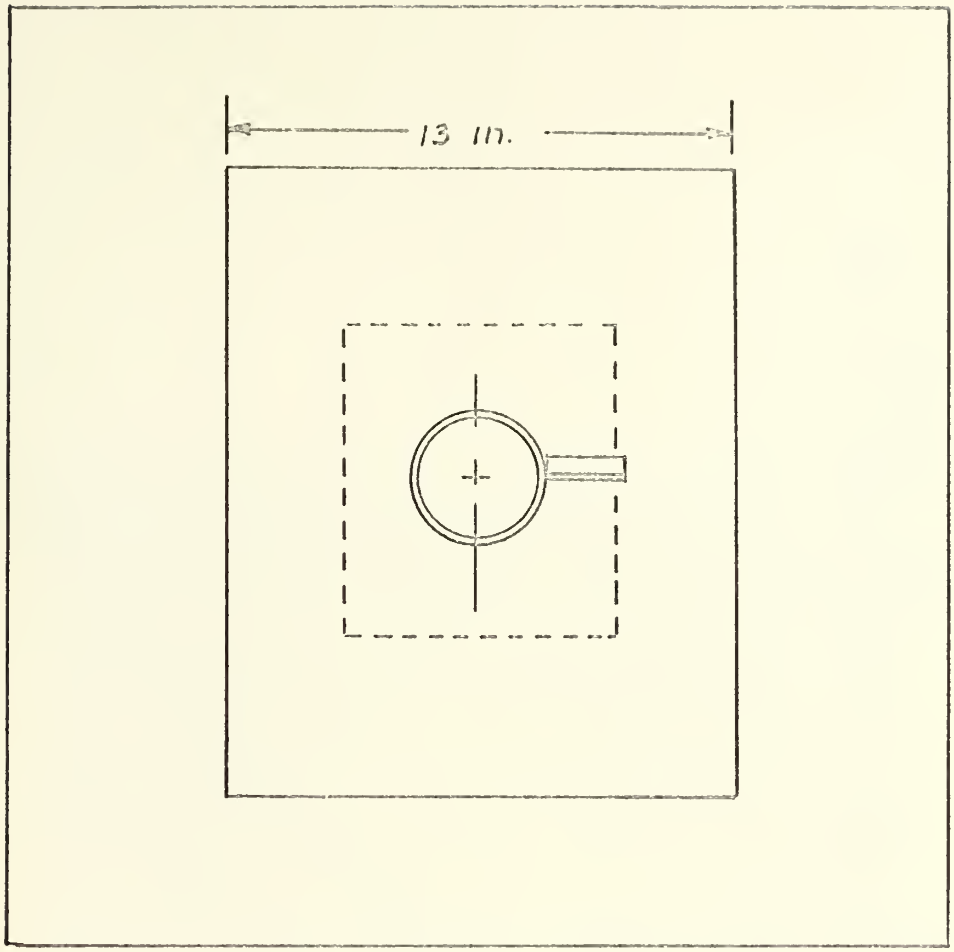


FIGURE 8 Arrangement of system for Calibration
(Dowward accelerated disk)



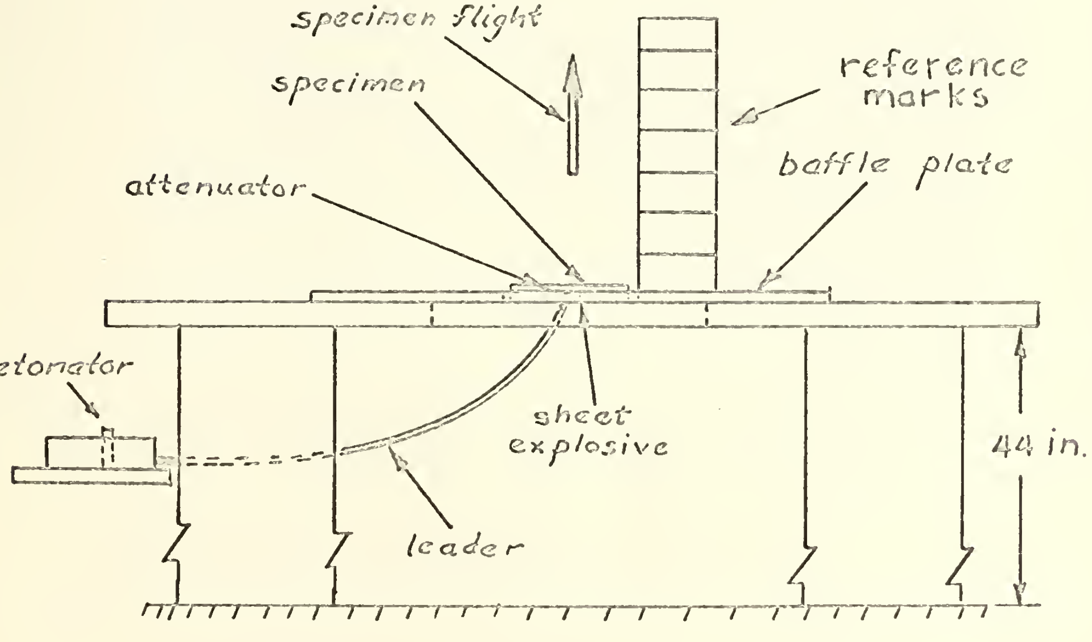


FIGURE 9. Calibration Arrangement
(Upward accelerated disk)

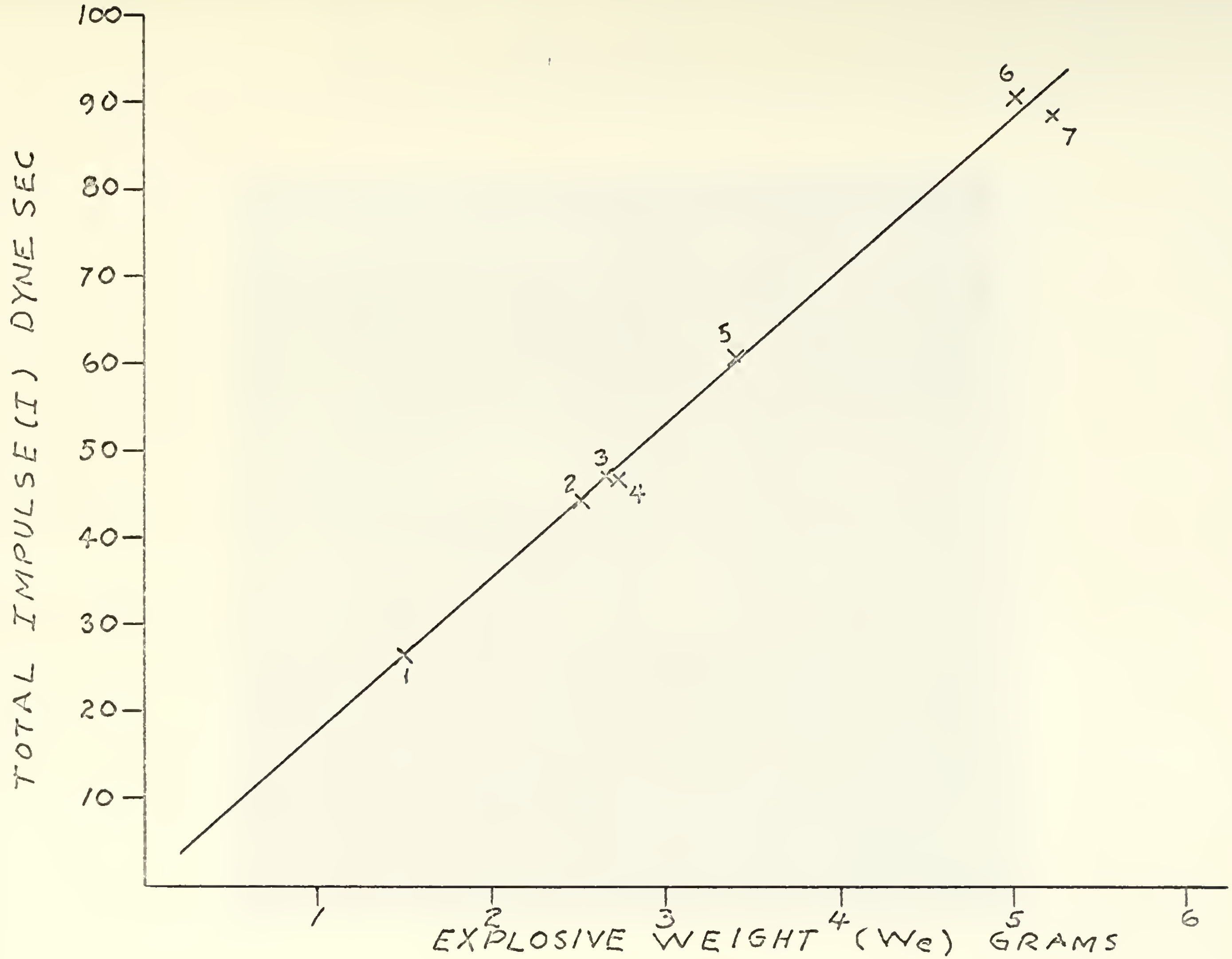


FIGURE 10. Total Impulse vs. Explosive Weight

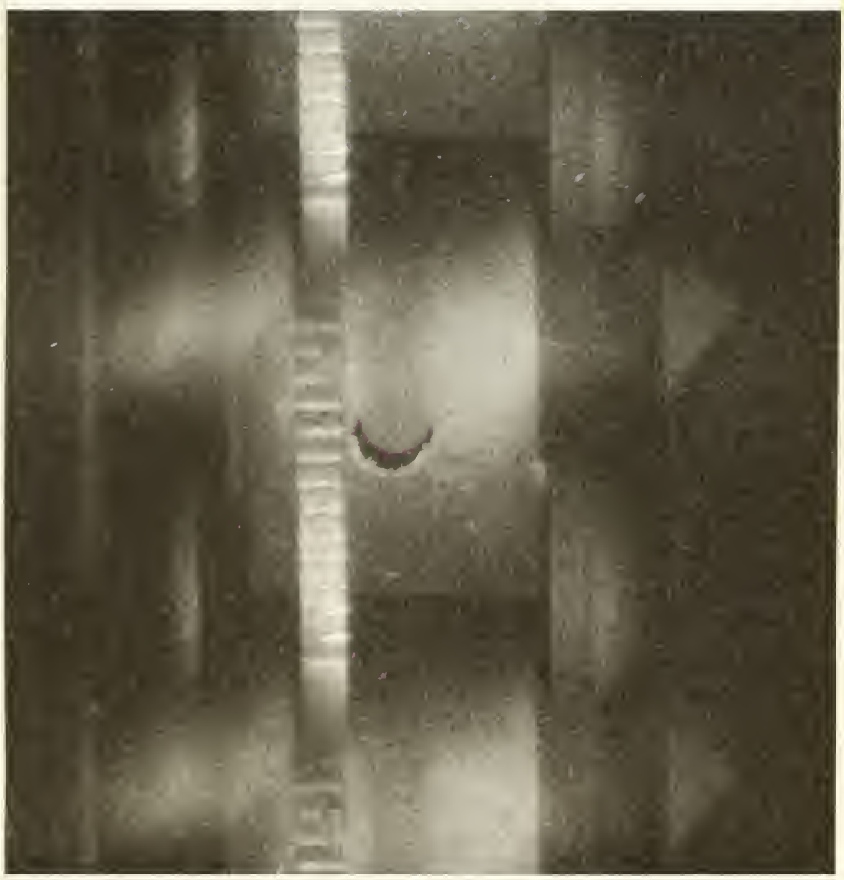
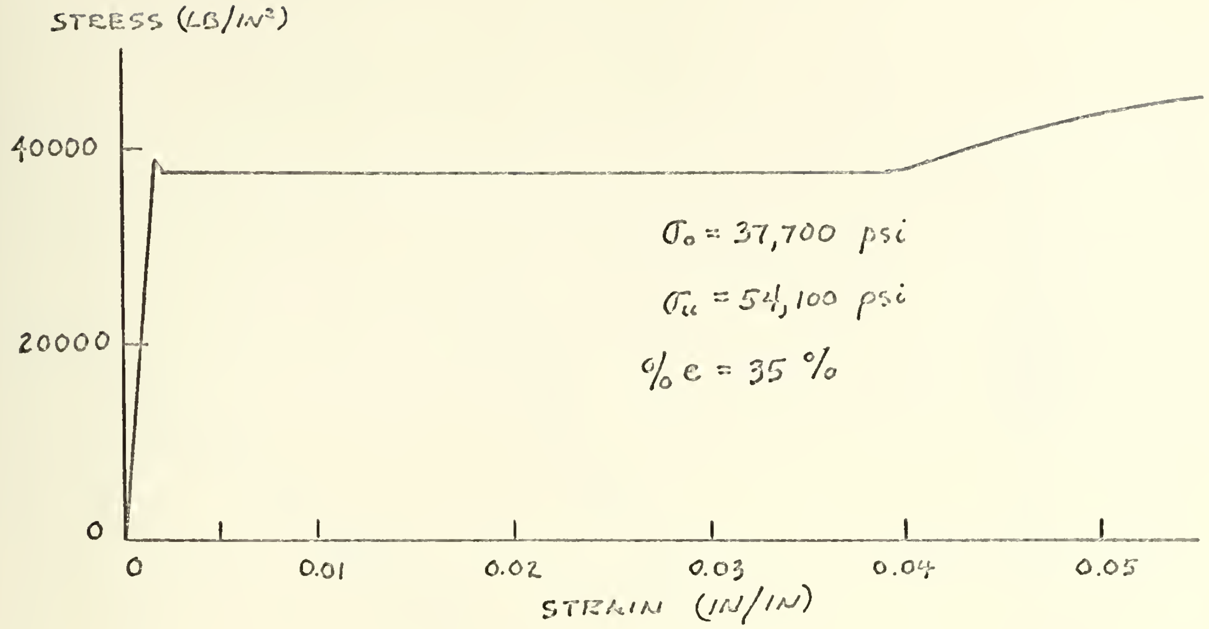
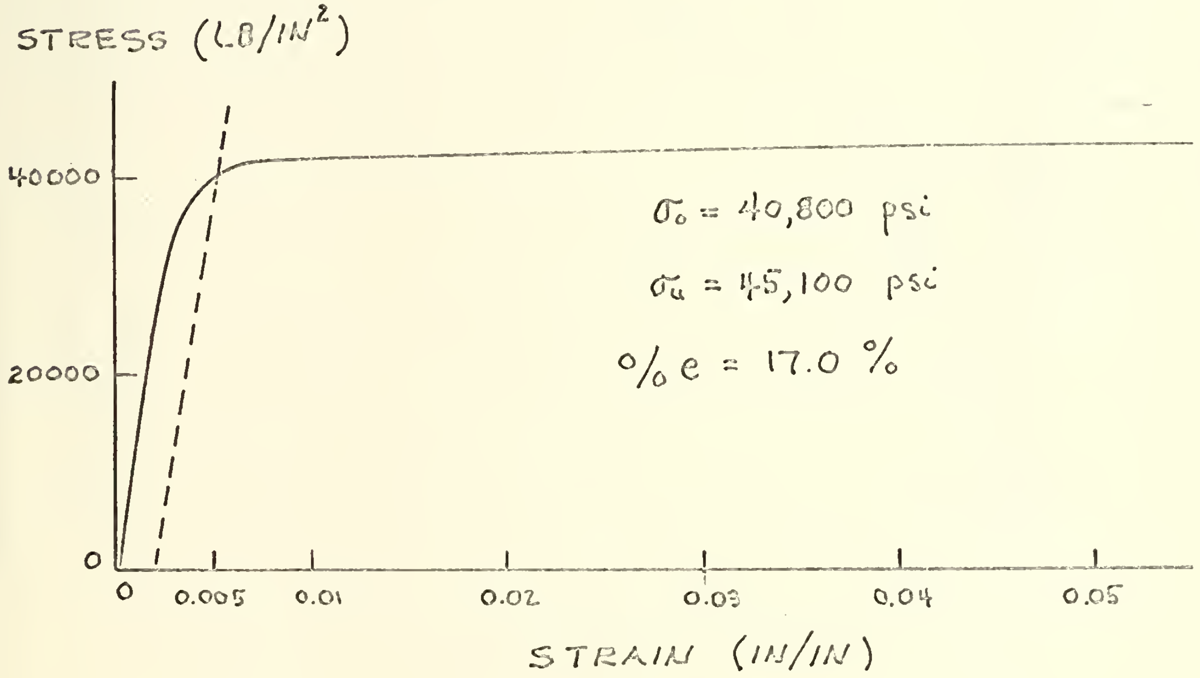


FIGURE 11 PHOTOGRAPH OF CYLINDRICAL PANEL CALIBRATION SPECIMEN IN FLIGHT (TEST NO. 29)



(a.) MILD STEEL



(b.) ALUMINUM 6061-T6

FIGURE 12

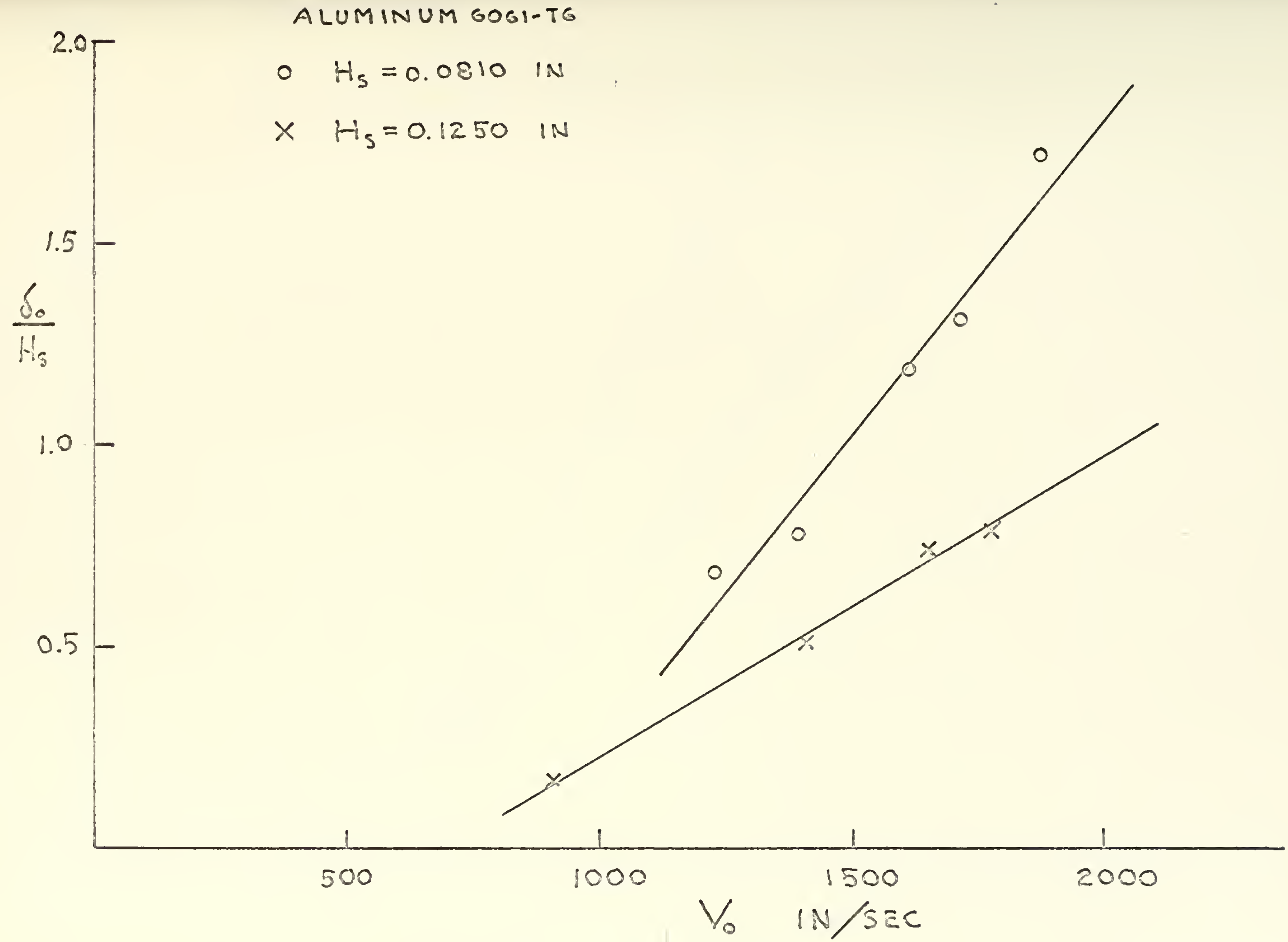

ALUMINUM 6061-T6
o H_s = 0.0810 IN
X H_s = 0.1250 IN
2.0
1.5
1.0
0.5
$\frac{\delta_o}{H_s}$
500
1000
1500
2000
V_o IN/SEC

FIGURE 13

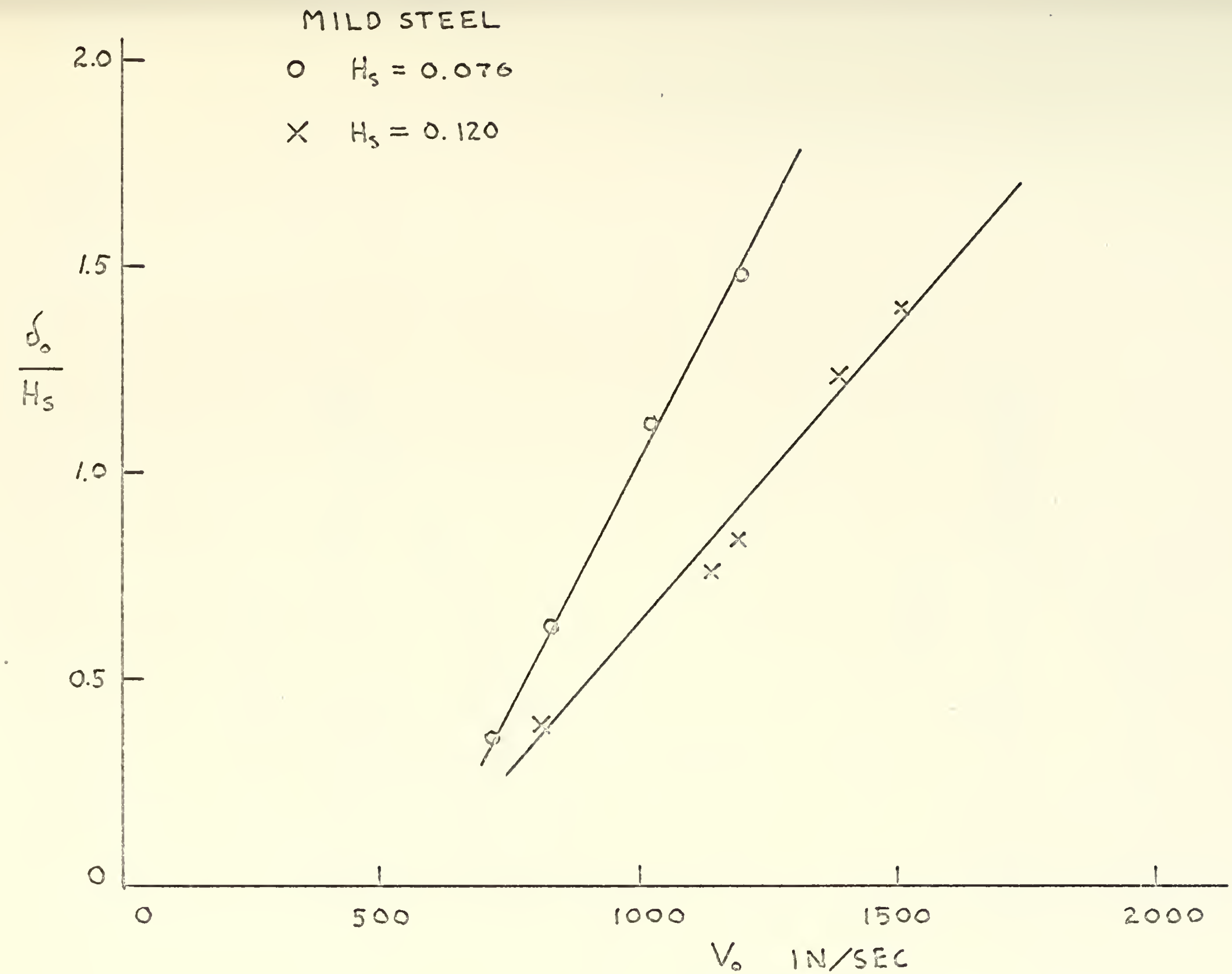
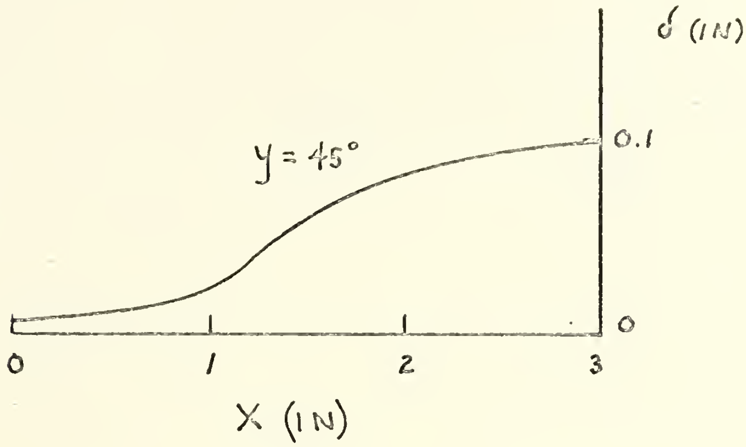

MILD STEEL
O $H_s = 0.076$
X $H_s = 0.120$
2.0
1.5
1.0
0.5
0
$\frac{\delta_o}{H_s}$
0
500
1000
1500
2000
V_o IN/SEC

FIGURE 14



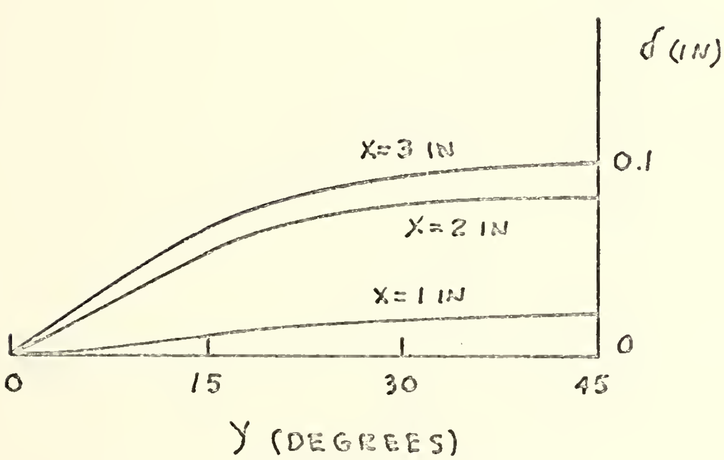


FIGURE 15a. Aluminum 6061-T6 Specimen No. 7 (90°)

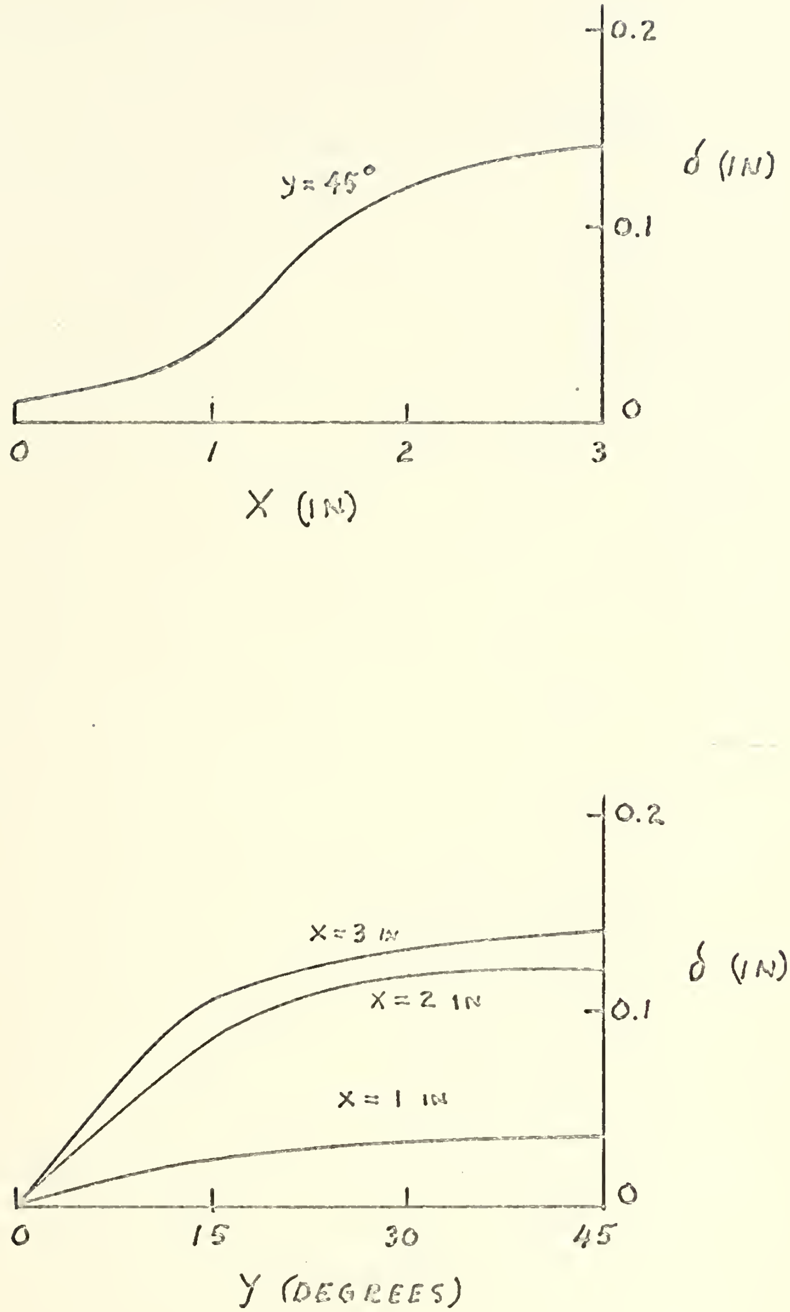
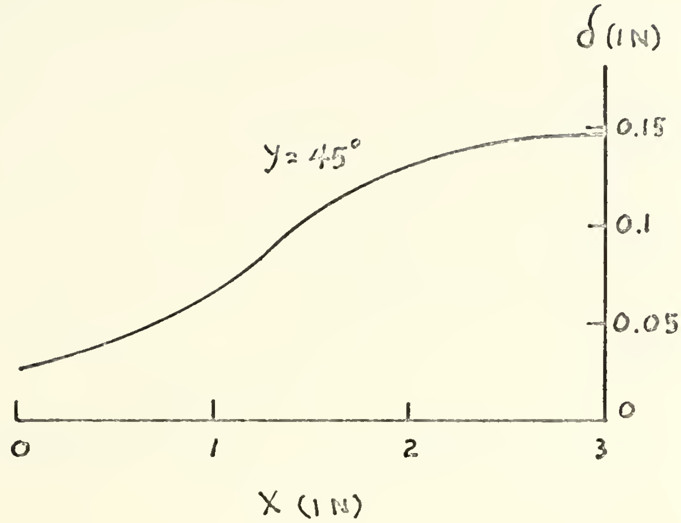


FIGURE 15b. Aluminum 6061-T6 Specimen No. 11 (90°)



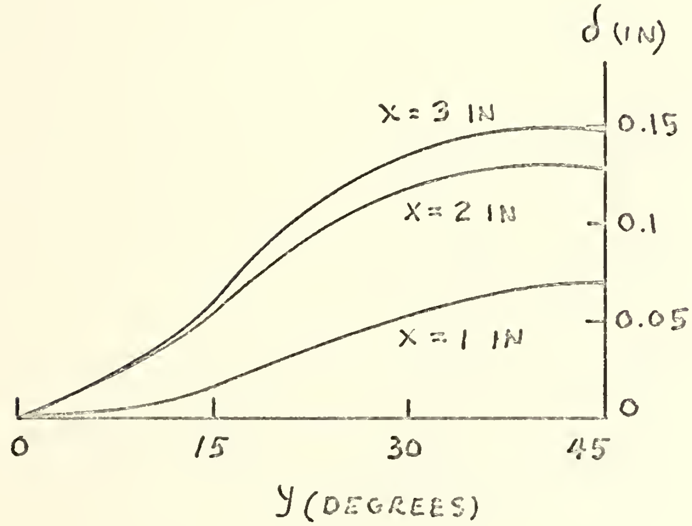
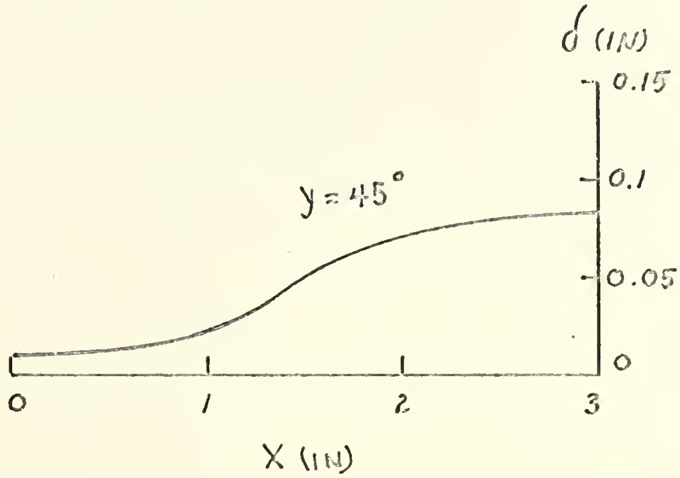


FIGURE 15c. Mild Steel Specimen No. 8 (90°)



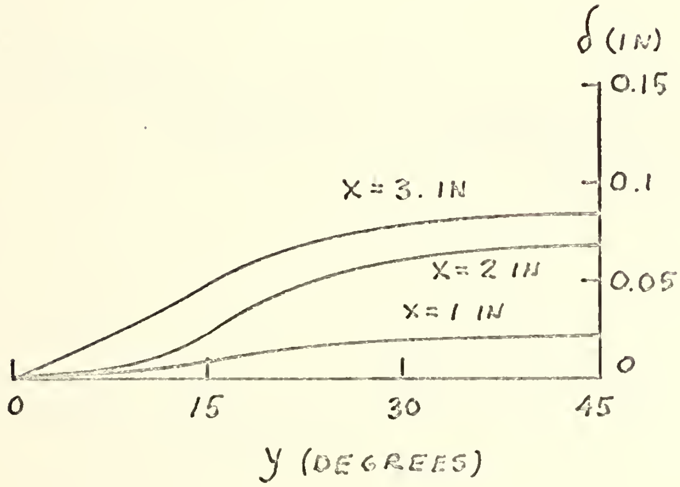


FIGURE 15d. Mild Steel Specimen No. 12 (90°)

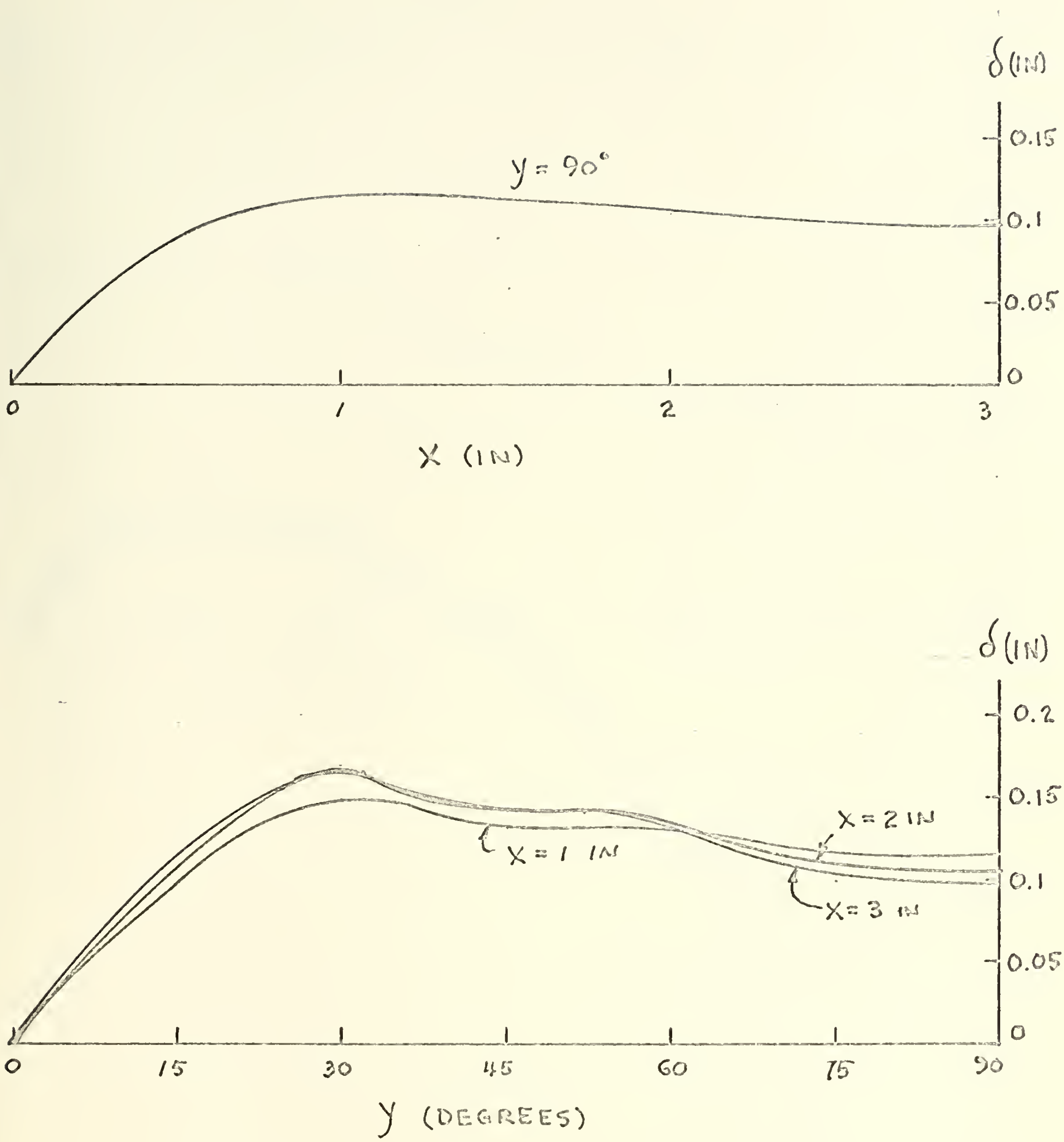


FIGURE 15e. Mild Steel Specimen No. 2 (180°)

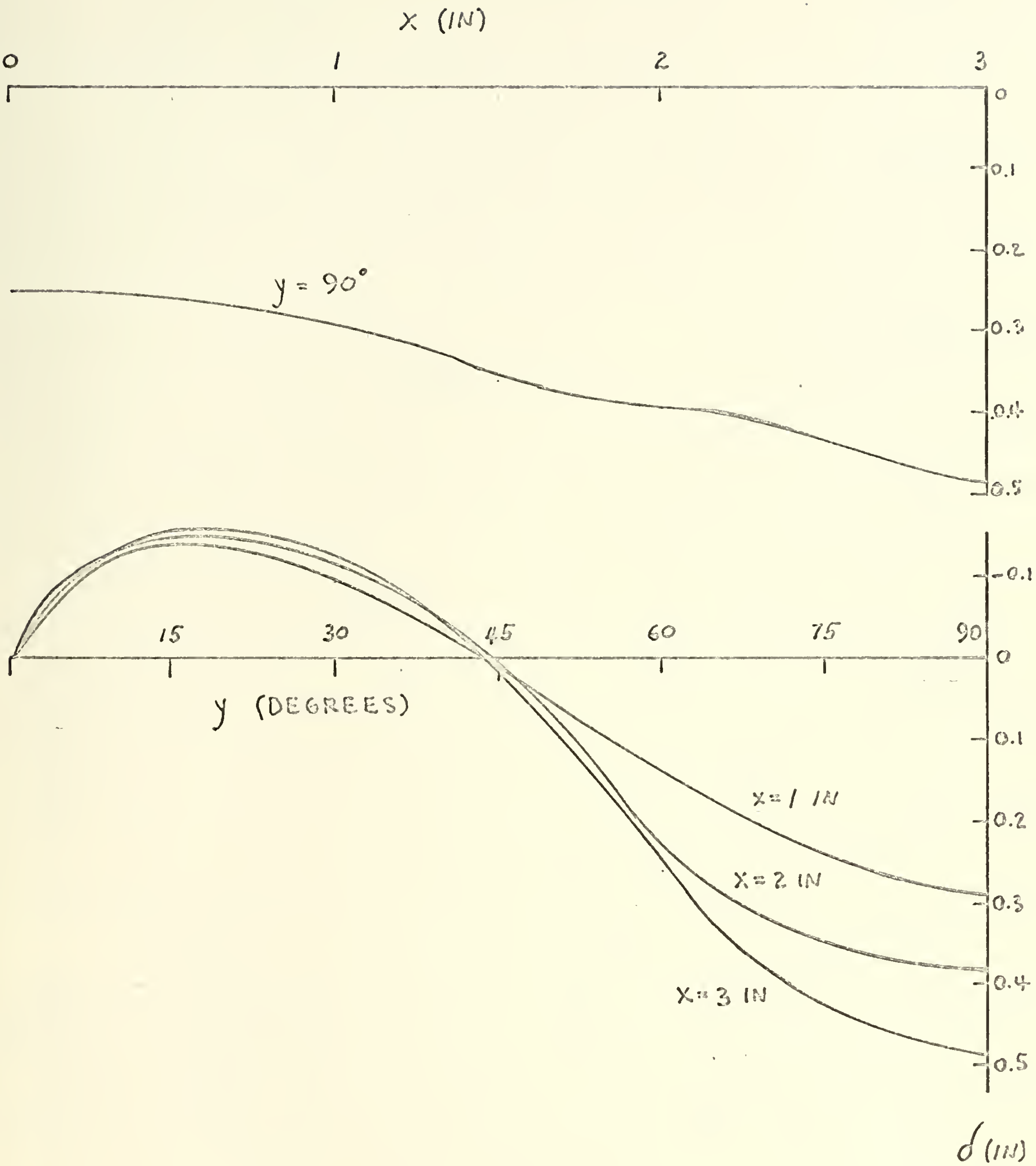
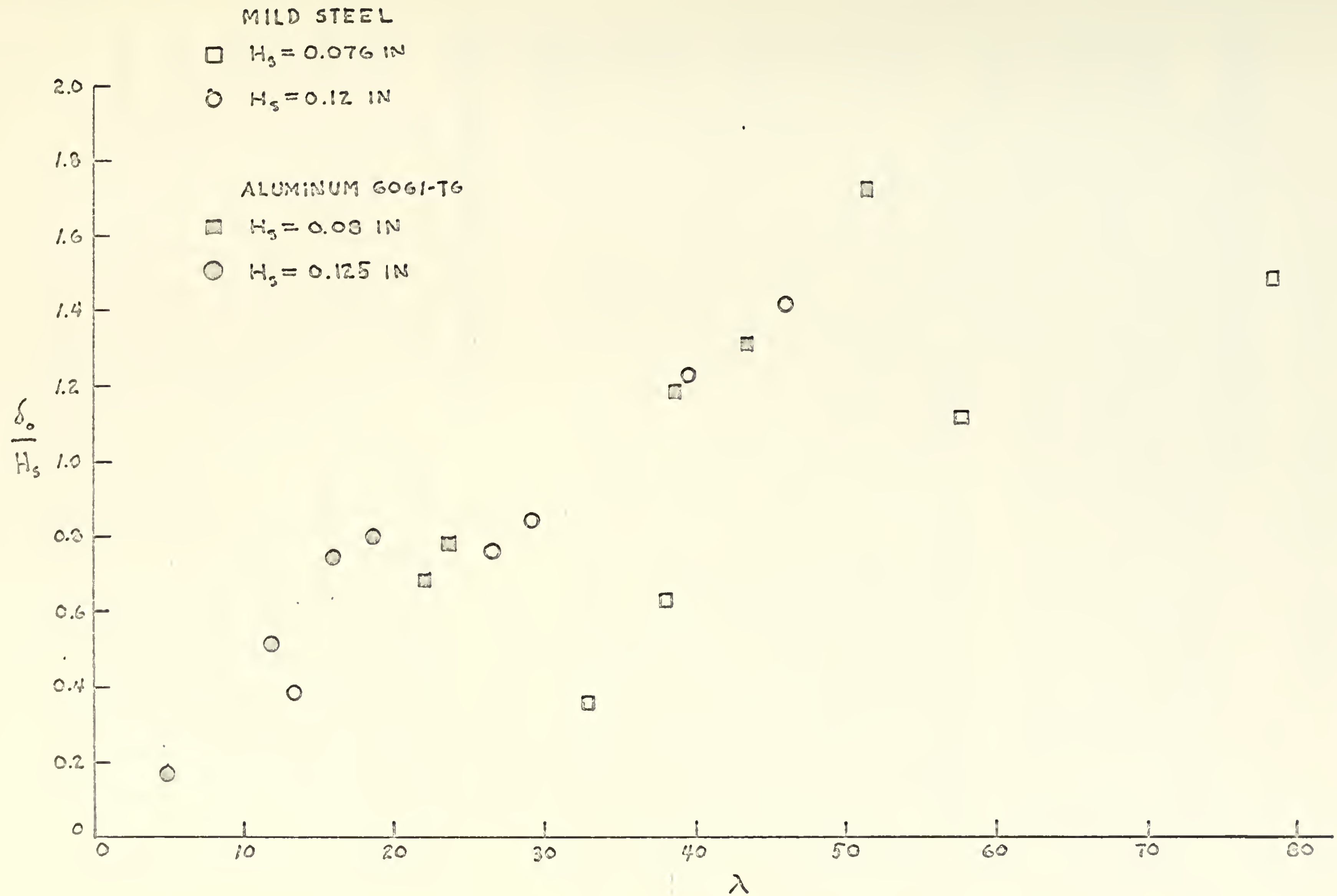


FIGURE 15f. Mild Steel Specimen No. 15 (180°)
(External Load)



MILD STEEL
H_s = 0.076 IN
H_s = 0.12 IN
ALUMINUM 6061-T6
H_s = 0.08 IN
H_s = 0.125 IN
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
δ_o / H_s
0
10
20
30
40
50
60
70
80
λ

FIGURE 16

APPENDIX A

CALIBRATION OF EXPLOSIVE IMPULSE

Preparation of the Explosive

The explosive used was DuPont "Detasheet" EL506D. Its composition is 63% pentaerythritol (PETN), 8% nitrocellulose, and the remainder an elastomeric binder. It was delivered in rectangular 10-inch by 20-inch sheets of .010, .015, and .030-inch thicknesses.

Each explosive sample was weighed to the nearest 0.01 gram. Its thickness was checked and found to vary a maximum of $\pm$.001 inches. The frequency of this thickness variation was high, so that effect of local thickness was considered negligible on the impulse per unit weight of explosive.

The specific impulse of the calibrated explosive allows the impulse of the explosive used in a particular experimental test to be determined by knowing the weight of the explosive.

The Calibration Procedure

The specific impulse of the explosive was determined by a series of calibration tests which were independent of the cylindrical panel experimental tests. The general method of calibration was that of measuring the velocity of a circular disk which had been accelerated either upward or downward by the explosive. The specific impulse of the explosive is related to the measured velocity by the formula:

$$I_o = \frac{M_s V_o}{W_e} \text{ dyne sec/g}$$

Most specimens were 1/8-inch thick, 3-inch diameter mild steel disks. However several 180-degree, 3-inch diameter cylindrical panels, and 3-inch chord, 5-inch diameter spherical caps were also tested in an attempt to estimate the effects of curvature of the specimens on specific impulse. Figure 7 illustrates the three types of calibration specimens.

Figure 4a presents the general arrangement of apparatus for the calibration tests. Figures 8 and 9 show detailed arrangements for tests of downward accelerated disks and upward accelerated disks, respectively. The velocity of the disk was determined by Fastax (Wollensak WF-2) framing camera. The camera was focused on the edge of the disk and photographed the first several inches of its flight. The disk was surrounded by a baffle plate ¼-inch from its edge so that smoke from the blast would be kept from the camera field of view. A layer of low density (.027 g/cm^3) foam rubber was placed with DuPont 4684 cement between the explosive sheet and the specimen. This foam attenuated the explosive and prevented pitting and spalling of the specimen surface. A strip of explosive 1/8-inch wide by 20--inches long was used as a leader from the specimen center to a No. 6 electric blasting cap which activated the explosive. The leader was .010-inches thick for .010-inch thick explosive and .015-inches thick when tests used greater than .010-inch explosive.

The camera time scale was provided by standard Fastax

time calibration pulses from a 1-KC frequency standard lighting a glow tube, the light from which was photographed on the film. The camera speed was approximately 12000 pictures per second (pps). One-hundred-foot rolls of Eastman Negative Type 7224 film or Kodak Reversal Type 7278 film were used, and the blast (event) was delayed until 0.7 seconds after the camera started. This delay allowed the camera to increase to sufficent speed for maximum number of pictures taken during the specimen flight.

Reference markers (graduated steel rule) exactly 1--inch apart were positioned parallel to the specimen flight path. The markers were close enough to the disk (1/16--inch) so that parallax could be neglected when the camera view was perpendicular to a line through the disk center and the reference markers.

Several assumptions were made in the impulse calibration tests. The edge of the disk was assumed to have the same velocity as its center. Departure of the disk from the vertical was assumed negligible. This appears to be a reasonably valid assumption from the photographs. Also, in at least two tests which were directed upward, the disk returned through the baffle hole. Interaction between the disk and the surrounding baffle was assumed neglible. It was also assumed that the chemical composition of the explosive remained constant. The effect of air drag on the specimen in a typical shot is shown to be negligible in Appendix B. The effects of rotation about the x and y axes

are calculated in tests where rotation is observed. A sample calculation is shown in Appendix C.

Results

Table A1 presents a summary of the results of the impulse calibration tests.

Test Nos. 1-4 were of downward accelerated disks. The specific impulse values varied greatly and are inconsistent with the values computed from later tests. It is thought that the procedure in these tests of using masking tape for supporting the specimens resulted in the loss of an indeterminate amount of energy and also excessive rotation of the specimens. This problem was solved in later tests by using two thin paper strips, approximately 1/8-inch wide, positioned across the baffle hole to support the specimen during the period immediately before the detonation.

Tests Nos. 12 and 13 used .030-inch explosive with an upward directed blast. The photographs were completely obscured by smoke. The baffles were apparently ineffective for the upward blasts using explosive greater than .020--inch thickness.

The cylindrical panel and spherical cap specimens resulted in values which were consistently within the range of values of I_o obtained from disk specimens. Test No. 25 photographs were completely obscured by smoke. Test No. 29 was below the range of I_o, but this could be partly due to the decrease in velocity at a distance 10-15 inches from its initial position. It is concluded that curvature effects

on the specific impulse within the range of explosive weights tested are very small and may be neglected.

Figure 10 shows the linear variation of impulse as a function of explosive weight. Table A2 presents the data plotted. Representative tests over the range of explosive weights used in the tests were plotted. This represents explosive thicknesses from .010 to .030-inches. It is seen that impulse increases linearly with explosive weight over the range of explosive calibrated.

Table A3 is a summary of the tests used for computing the final average specific impulse. Other tests were disregarded for reasons of inconsistences due to rotation or photographs obscured by smoke. Also, tests using curved specimens were not used in the final average value. The ten tests used were all disks, five accelerated upward and five accelerated downward, and the resulting average specific impulse was found to be 17.69×10^4 dyne sec/g. This value compares to a specific impulse of 18.52×10^4 dyne sec/g reported in the Picatinny Arsenal experiments (18). However, the latter experiments did not account for the effects of gravity and all tests were of downward accelerated specimens. Neglecting gravity, the average specific impulse of the five tests accelerated downward (Test Nos. 14, 15, 16, 19, and 20) is found to be 18.28×10^4 dyne sec/g.

In comparing the results here with those of reference (18), the fact that in reference (18), the explosive was

detonated at one end of the specimen instead of at the specimen center, should be considered. With this in mind, the results, neglecting gravity, reported here compare favorably to the results reported in reference (18).

A typical framing camera photograph of a cylindrical panel specimen in flight is presented in Figure 11.

TABLE A1

SUMMARY OF IMPULSE CALIBRATION RESULTS

Test No.	M_s g	W_e g	H_e in	Spec. Geom.	Blast Dir.	ϕ_x rad	ϕ_y rad	Remarks
1	105.85	2.95	.020	Disk	Down	0.4π	0.75π	1,2
2	106.15	1.47	.010	Disk	Down	0.3π		1,2
3	105.20	2.98	.020	Disk	Down	0.2π	0.09π	1,2
4	105.10	1.50	.010	Disk	Down		2π	1,2
5	105.25	1.67	.010	Disk	Down			3
6	106.17	3.22	.020	Disk	Up	0.2π	0.4π	2
7	106.15	1.53	.010	Disk	Up	0.2π	0.3π	2
8*	105.48	1.50	.010	Disk	Up			
9	105.55	3.20	.020	Disk	Up	0.3π	0.4π	2
10*	107.02	2.68	.015	Disk	Up			
11*	106.27	2.64	.015	Disk	Up			
12	107.33	4.95	.030	Disk	Up			4
13	107.02	5.00	.030	Disk	Up			4
14*	107.02	2.65	.015	Disk	Down			5
15*	105.87	2.63	.015	Disk	Down			5
16*	105.87	2.67	.015	Disk	Down			5
17	417.8	3.42	.015	Cyl.	Up			6
18	414.2	3.40	.015	Cyl.	Up			7
19*	106.58	2.72	.020	Disk	Down			5
20*	105.70	2.51	.015	Disk	Down			5
21	102.42	2.59	.015	Cap.	Down			5
22*	106.23	2.7	.020	Disk	Up			
23*	105.90	2.69	.020	Disk	Up			
24	131.85	3.13	.015	Cap.	Up			7
25	413.5	3.48	.015	Cyl.	Up			
26	107.77	5.22	.030	Disk	Down			
27	106.84	5.00	.030	Disk	Down			
28	107.51	7.94	.045	Disk	Down			8
29	413.5	6.90	.030	Cyl.	Down			

TABLE A1 (continued)

Test No.	n	h_n in	t_n msec	$2gh_n$ cm/sec	V_n cm/sec	V_o cm/sec	I_o 10^4dyne sec/g
	1	3.0	1.86	122.6	3977.4		
	2	3.5	2.11	132.8	4087.2		
1	3	4.0	2.36	142.1	4167.9	4149.8	15.89
	4	4.5	2.61	150.6	4229.4		
	5	5.0	2.86	159.2	4280.8		
	6	6.0	3.52	174.1	4155.9		
	1	3.0	3.85	122.6	1857.4		
	2	3.5	4.51	132.8	1837.2		
2	3	4.0	5.18	142.1	1817.9	1812.3	13.29
	4	4.5	5.84	150.6	1809.4		
	5	5.0	6.51	159.2	1790.8		
	6	6.0	7.89	174.1	1760.9		
	1	4.0	2.28	142.1	4317.9		
	2	4.5	2.61	150.6	4229.4		
3	3	5.0	2.94	159.2	4160.4	4210.0	14.97
	4	5.5	3.19	166.7	4133.3		
	1	3.0	6.53	122.6	1045.4		
	2	3.5	7.70	132.8	1022.2		
4	3	4.0	8.70	142.1	1025.9	1027.5	9.52
	4	4.5	9.55	150.6	1047.9		
	5	5.0	10.55	159.2	1042.8		
	6	6.0	13.20	174.1	983.9		
	1	3.75	2.03	137.3	4827.3		
	2	4.25	2.28	146.4	4876.4		
6	3	4.75	2.53	154.7	4914.7	4944.4	16.65
	4	5.25	2.78	162.9	4962.9		
	5	5.75	3.03	170.4	4990.4		
	6	6.75	3.49	184.5	5094.5		
	1	2.75	3.13	117.8	2352.8		
	2	3.25	3.63	128.0	2403.0		
7	3	3.75	4.13	137.3	2442.3	2416.6	16.88
	4	4.25	4.71	146.4	2436.4		
	5	4.75	5.29	154.7	2434.7		
	6	5.75	6.46	170.4	2430.4		
	1	5.75	4.05	137.3	2487.3		
	2	4.25	4.55	146.4	2521.4		
8	3	4.75	5.05	154.7	2544.7	2542.5	17.88
	4	5.25	5.55	162.9	2562.9		
	5	5.75	6.13	170.4	2552.4		
	6	6.75	7.13	184.5	2586.5		

TABLE A1 (continued)

Test No.	n	h_n in	t_n msec	$2gh_n$ cm/sec	V_n cm/sec	V_o cm/sec	I_o 10^4dyne sec/g
	1	3.25	1.69	128.0	4988.0		
	2	3.75	1.86	137.3	5205.8		
9	3	4.25	2.19	146.4	5076.4	5151.6	17.45
	4	4.75	2.36	154.7	5274.7		
	5	5.25	2.60	162.9	5302.7		
	6	5.75	3.02	170.4	5010.4		
	1	3.25	2.03	128.0	4198.0		
	2	3.75	2.20	137.3	4467.3		
10	3	4.25	2.45	146.4	4556.4	4487.5	17.93
	4	4.75	2.70	154.7	4614.7		
	5	5.25	3.03	162.9	4567.9		
	6	5.75	3.36	170.4	4520.4		
	1	2.75	1.7	117.8	4227.6		
	2	3.25	1.95	128.0	4358.0		
11	3	3.75	2.20	137.3	4467.3	4457.4	17.95
	4	4.25	2.45	146.4	4556.4		
	5	4.75	2.70	154.7	4624.7		
	6	5.75	3.36	170.4	4510.4		
	1	3.0	1.7	122.6	4357.4		
	2	3.5	1.75	132.8	4427.2		
14	3	4.0	2.20	142.1	4477.9	4417.3	17.84
	4	4.5	2.45	150.6	4509.4		
	5	5.0	2.76	159.2	4445.8		
	6	6.0	3.42	174.1	4285.9		
	1	3.0	1.7	122.6	4357.4		
	2	3.5	1.95	132.8	4427.2		
15	3	4.0	2.2	142.1	4477.9	4447.0	17.91
	4	4.5	2.45	150.6	4509.4		
	5	5.0	2.70	159.2	4545.8		
	6	6.0	3.36	174.1	4365.9		
16	1	5.0	2.70	159.2	4540.8	4513.3	17.96
	2	6.0	3.20	174.1	4585.9		
	1	2.0	3.87	100.3	1413.3		
	2	3.0	5.70	122.6	1462.6		
18	3	4.0	7.53	142.1	1492.1	1468.2	17.89
	4	5.0	9.53	159.2	1494.2		
	5	6.0	11.69	174.1	1479.1		
	1	3.0	1.72	122.6	4307.4		
	2	3.5	1.88	132.8	4597.2		
19	3	4.0	2.21	142.1	4457.9	4354.8	17.07

TABLE A1 (continued)

Test No.	n	h_n in	t_n msec	$2gh_n$ cm/sec	V_n cm/sec	V_o cm/sec	I_o 10^4dyne sec/g
19	4	4.5	2.54	150.6	4349.4		
	5	5.0	2.87	159.2	4270.8		
	6	6.0	3.53	174.1	4145.9		
	1	3.0	1.86	122.6	3977.4		
	2	3.5	2.11	132.8	4087.2		
20	3	4.0	2.36	142.1	4167.9	4149.8	17.48
	4	4.5	2.61	150.6	4229.4		
	5	5.0	2.86	159.2	4280.8		
	6	6.0	3.52	174.1	4155.9		
	1	3.0	1.80	122.6	4157.4		
	2	3.5	2.03	132.8	4247.2		
21	3	4.0	2.28	142.1	4317.9	4294.8	1698
	4	4.5	2.53	150.6	4379.4		
	5	5.0	2.78	159.2	4400.8		
	6	6.0	3.44	174.1	4265.9		
	1	3.25	1.95	128.0	4358.0		
	2	3.75	2.20	137.3	4467.3		
22	3	4.25	2.45	146.4	4546.4	4564.9	17.95
	4	4.75	2.70	154.7	4614.7		
	5	5.25	2.95	162.9	4672.9		
	6	5.75	3.20	170.4	4730.4		
	1	3.25	2.05	128.0	4158.0		
	2	3.75	2.30	137.3	4277.3		
23	3	4.25	2.55	146.4	4386.4	4297.9	16.92
	4	4.75	2.88	154.7	4344.7		
	5	5.25	3.21	170.4	4322.9		
	1	3.0	1.70	122.6	4595.0		
	2	3.5	1.95	132.8	4691.8		
24	3	4.0	2.20	142.1	4760.3	4777.1	17.38
	4	4.5	2.45	150.6	4815.9		
	5	5.0	2.70	159.2	4862.9		
	6	6.0	3.20	174.1	4936.6		
	1	10.0	2.95	223.3	8386.9		
	2	12.0	3.61	244.5	8198.7	8152.7	16.83
26	3	14.0	4.27	264.1	8063.8		
	4	16.0	4.93	282.3	7961.3		
	1	9.0	2.53	211.7	8823.9		
27	2	11.0	3.19	233.3	8525.3	8456.8	18.07
	3	13.0	3.85	254.5	8322.1		
	4	16.0	4.84	282.3	8155.7		

TABLE A1 (continued)

Test No.	n	h_n in	t_n msec	2ghn cm/sec	V_n cm/sec	V_o cm/sec	I_o 10^4dyne sec/g
	1	10.0	10.37	223.3	2487.5		
29	2	12.0	12.37	244.5	2436.2	2395.4	14.36
	3	14.0	14.54	264.1	2362.2		
	4	15.0	15.78	282.3	2295.5		

Final average specific impulse $I_o = 17.69 \times 10^4$ dyne sec/g

$= 0.3977$ lb sec/g

REMARKS CODE for TABLE A1

*	in column 1 indicates that resulting specific impulse for the test is inculded in calculation of final average specific impulse
1	specimen held by masking tape before detonation
2	rotation about x-axis (ϕ_x) is approximate
3	explosive only partially detonated - no results
4	photographs obscured by smoke - no results
5	specimen rested on paper strips before detonation
6	photographs not taken of event - no results
7	rotation slight but negligible
8	specimen accelerated at large angle from vertical -- no results

TABLE A2

DATA FOR FIGURE 10. TOTAL IMPULSE VS. EXPLOSIVE WEIGHT

Point No.	Test No.	W_e g	I 10^4 dyne sec
1	8	1.5	26.82
2	20	2.51	43.87
3	11	2.64	47.39
4	19	2.72	46.43
5	18	3.4	60.83
6	27	5.00	90.35
7	26	5.22	87.86

TABLE A3

SUMMARY OF CALIBRATION DATA USED
IN FINAL SPECIFIC IMPULSE

Test No.	Disk Direction	I_o 10^4 dyne sec/g
8	Up	17.88
10	Up	17.93
11	Up	17.95
14	Down	17.84
15	Down	17.91
16	Down	17.96
19	Down	17.07
20	Down	17.48
22	Up	17.95
23	Up	16.92

Average specific impulse = 17.69×10^4 dyne sec/g

= 0.3977 lb sec/g

APPENDIX B

THE EFFECT OF AIR DRAG ON IMPULSE CALIBRATION

The reduction due to air drag of the specific impulse imparted by sheet explosive to a flat circular disk specimen is calculated. From reference (19), the formula for drag force is:

$$D = C_d \rho \frac{V_o^2}{2} A$$

Where

D = drag force

C_d = drag coefficient

ρ = density of air at $75^{\circ}F$

A = area of disk normal to air flow

For a circular disk normal to flow, and Reynolds No. $(Re) > 10^3$,

$C_d = 1.12$ (ref. 19.)

Also

$\rho = 2.22 \times 10^{-3}$ lb sec^2/ft^4

$\nu = 180 \times 10^{-6}$ ft^2/sec

<u>Sample Calculation for Test No. 9</u>

$d = 3$ in

$V_o = 5095.4$ cm/sec;

$I_o = 17.1 \times 10^4$ dyne sec/g

$M_s = 105.55$ g

$$A = \frac{\pi d^2}{4}$$

$$= \frac{\pi (3)(2.54)^2}{4}$$

$$= 45.6 \text{ cm}^2$$

$$Re = \frac{V_o d}{\nu}$$

$$= \frac{5095.4(3)(2.54)}{180 \times 10^{-6}(144)(2.54)^2}$$

$$= 2.32 \times 10^5$$

$$> 10^3$$

therefore

$$C_d = 1.12$$

Now

$$D = C_d \rho \frac{V_o^2}{2} A$$

$$= 1.12(2.22 \times 10^{-3} \text{ slug/ft}^3)(1.459 \times 10^4 \text{ g/slug}) \times \frac{1}{(30.48)^3} \frac{\text{ft}^3}{\text{cm}^3} \times \frac{(5094.4)^2}{2} \frac{\text{cm}^2}{\text{sec}^2} \times 45.6\text{cm}^2 = 7.58 \times 10^5 \text{ g cm/sec}^2$$

For six inches travel

$$KE = D \times 6\text{in} \times 2.54\text{cm/in}$$

$$= 7.58 \times 10^5 \times 6 \times 2.54$$

$$= 115.57 \text{ g cm}^2/\text{sec}^2$$

If this KE is assumed to be translational,

$$1/2\ M_s V_o^2 = 115.57 \text{ g cm}^2/\text{sec}^2$$

$$V_o = \frac{2(115.57)}{105.55}$$

$$= 1.48 \text{ cm/sec}$$

The increase in specific impulse, if no air drag, is

$$I_o(\text{increase}) = \frac{M_s V_o}{W_e}$$

$$= \frac{105.55(1.48)}{3.2}$$

$$= 0.004882 \times 10^4 \text{ dyne sec/g}$$

This increase is negligible when compared to the orginally calculated $I_o = 17.45 \times 10^4$ dyne sec/g in Test No. 9.

Thus it is shown that the effect of air drag on the specific impulse is negligible in the range of explosive impulse calibrated in this report.

This increase is negligible when compared to the originally calculated $I_o = 17.86 \times 10^6$ dyne-sec/g in Task No. 4.

Thus it is shown that the effect of air drag on the specific impulse is negligible in the range of explosive impulse calibrated in this report.

APPENDIX C

THE EFFECT OF SPECIMEN ROTATION ON IMPULSE CALIBRATION

The total kinetic energy (KE) of the disk in free-flight is the sum of its translational energy and the energies of rotation about its x, y, and z axes. The equation is

$$KE = M_s V_o{}^2/2 = (I_x\omega_x^2 + I_y\omega_y^2 + I_z\omega_z^2)/2$$

In all cases, rotation about the z-axis was neglected ($\omega_z \approx 0$). Due to symmetry, the moments of inertia about x and y axes are equal ($I_x = I_y = I$). Thus, above equation becomes:

$$KE = M_s V_o{}^2/2 + I(\omega_x{}^2 + \omega_y{}^2)/2$$

The disk moment of inertia (I) is derived from

$$I = \sum_{n=1}^{\infty} m_n k_n{}^2$$

where

$$m = \rho\, dv$$
$$= \rho\, r d\theta dr H_s$$
$$k = r \sin\theta$$

Then

$$I = 2\int_0^{\pi}\int_0^{a} \rho H_e r^3 \sin^2\theta\, dr\, d\theta$$
$$= 2\rho H_e \int_0^{\pi} r^4/4 \Big|_0^{a} \sin^2\theta\, d\theta$$
$$= \rho H_e a^4/2 \int_0^{\pi} \sin^2\theta\, d\theta$$
$$= \rho H_e a^4/4 \left[\theta - \sin 2\theta)/2\right]_0^{\pi}$$
$$= \rho \frac{H_e a^4 \pi}{4}$$
$$= M_s a^2/4 \text{ g cm}^2$$

The angular velocity about x-axis or y-axis (x,y) for the initial six inches travel is then calculated by

$$\omega_{x,y} = \frac{\phi_{x,y} V_o}{6 \times 2.54} \text{ sec}^{-1}$$

Sample Calculation - Test No. 9

$$M_s = 105.55 \text{ g}$$

$$I_o = 17.1 \times 10^4 \text{ dyne sec/g}$$

$$V_o = 5151.6 \text{ cm/sec}$$

$$a = 1.5 \text{ in} \times 2.54 \text{ cm/in}$$

$$= 3.81 \text{ cm}$$

$$\phi x = .3\pi \text{ radians}$$

$$\phi y = .4\pi \text{ radians}$$

$$I = \frac{M_s a^2}{4}$$

$$= \frac{105.55(3.81)^2}{4}$$

$$= 383.04 \text{ g cm}^2$$

$$\omega x^2 = \left[\frac{0.3\pi(5151.6)}{(6)(2.54)}\right]^2$$

$$= 10.150 \times 10^4 \text{ sec}^{-2}$$

$$\omega y^2 = \left[\frac{0.4\pi(5151.6)}{6(2.54)}\right]^2$$

$$= 17.954 \times 10^4 \text{ sec}^{-2}$$

$$KE = M_s V_o^2/2 + I(\omega x^2 + \omega y^2)/2$$

$$= 105.55(5151.6)^2/2 + 383.04(10.150 \times 10^4$$

$$+ 17.954 \times 10^4)/2 \text{ g cm}^2/\text{sec}^2 \text{ or ergs}$$

$$= 1.424 \times 10^9 + .053825 \times 10^9$$

$$= 1.4778 \times 10^9 \text{ ergs}$$

If this total KE were translational energy then

$$\tfrac{1}{2} M_s V_o^2 = 1.4778 \times 10^9$$

$$V_o^2 = 2(1.4778 \times 10^9)/105.55$$

$$V_o = 5291.7 \text{ cm/sec}$$

This is an increase of 140.1 cm/sec over original

$$V_o = 5151.6 \text{ cm/sec}$$

The corrected specific impulse is

$$I_o = \frac{M_s V_o}{W_e}$$

$$= \frac{105.55(5192.6)}{3.2}$$

$$= 17.45 \times 10^4 \text{ dyne sec/g}$$

This is an increase of 0.45×10^4 dyne sec/g over the originally calculated $I_o = 17.00 \times 10^4$ dyne sec/g.

Thus it is shown that the effect of specimen rotation on specific impulse of explosive is typically small as a percent of the impulse computed neglecting rotation. However, the effect is not negligible and must be considered in the final specific impulse. Tests in this report where rotation was observed were not regarded in the final average specific impulse.

APPENDIX D

MECHANICAL PROPERTIES

OF SPECIMEN MATERIALS

Tensile tests on the specimen materials were conducted on an Instron testing machine. The average strain-rate used in the tests was 0.02 in/in/min.

For the materials used in the 90-degree specimens, the values used are averages of the results obtained from specimens cut with and across the grain. The 180-degree tensile specimens were cut from the original cylinders in the axial direction.

The important values determined for this study are yield stress (σ_o) ultimate tensile stress (σ_u) and percent elongation ($\% e$).

The yield stress found here is the 0.2% offset yield strength. This means that if the specimen is loaded to the yield stress, then unloaded, the length will be 0.2% greater than the original gage length. The gage length was 1-inch in all tensile tests.

The ultimate tensile stress is the maximum stress that can be sustained by the material, the highest value on the stress-strain curve. Typical stress-strain curves are shown in Figure 12.

Percent elongation is the ratio of increase in gage length to original gage length at the point of fracture. It is used to compare the ductility of the materials.

The resulting properties obtained from the tensile tests on aluminum 6061-T6 and mild steel specimens are presented in Tables D1 and D2. The higher values of σ_0 represent the specimens cut with the grain of the material. The percentage difference between σ_0 of specimens cut with the grain and across the grain ranges from 2.72% for aluminum 6061-T6 of 0.125-inch thickness to 7.38% for mild steel of 0.076-inch thickness.

TABLE D1

MECHANICAL PROPERTIES OF ALUMINUM 6061-T6

Cylinder Size	Nominal Thickness	σ_o	σ_u	% e
deg	in	psi	psi	%
180	.117	36,000	42,000	12.3
180	.1525	38,600	44,100	15.1
90	.1250	40,800	45,100	17.0
90	.1250	41,900	45,200	17.0
90	.080	38,000	43,300	16.5
90	.080	40,700	45,100	16.8

TABLE D2

MECHANICAL PROPERTIES OF MILD STEEL

Cylinder Size	Nominal Thickness	σ_o	σ_u	% e
deg	in	psi	psi	%
180	.160	51,700	57,000	18.0
90	.120	36,100	51,600	35.0
90	.120	37,700	54,100	29.0
90	.076	33,900	49,500	28.0
90	.076	36,600	52,000	30.0

REFERENCES

(1) Symonds, P. S., "Survey of Methods of Analysis for Plastic Deformation of Structure Under Dynamic Loading," Brown University Report BU/NSRDC/1-67, June 1967.

(2) Hodge, P. G., "The Influence of Blast Characteristic on the Final Deformation of Circular Cylindrical Shells," Journal of Applied Mechanics, Vol. 23, 1956, Trans. ASME Vol. 78, pp. 617-624.

(3) Hodge, P. G., "Impact Pressure Loading of Rigid-Plastic Cylindrical Shells," Journal of Mech. Phys. Solids, 1955 Vol. 3, pp. 176-188.

(4) Hodge, P. G., "Effect of End Conditions on Dynamic Loading of Plastic Shells," Journal of Mech. Phys. Solids, Vol. 7 No. 4, October 1959, pp. 258-263.

(5) Eason, G., and Shield, R. T., "Dynamic Loading of Rigid--Plastic Cylindrical Shells," Journal of Mech. Phys. Solids, Vol. 4, 1956, pp. 53-71.

(6) Hodge, P. G., and Paul, B., "Approximate Yield Conditions in Dynamic Plasticity," Proc. Third Midwestern Conference on Solid Mechs., 1957, pp. 29-47.

(7) Duszek, M., "Plastic Analysis of Cylindrical Shells Subjected to Large Deflections," Arch. Mech. Stos., Vol. 18, 1966, pp. 599-614.

(8) Jones, N., "The Influence of Large Deflections on the Behavior of Rigid-Plastic Cylindrical Shells Loaded Impulsively," Mass. Inst. of Tech. Dept. of Nav. Arch. and Marine Engr., Report No. 68-21, Cambridge, Mass. , Nov. 1968.

(9) Humphreys, J. S., "Plastic Deformation of Impulsively Loaded Straight Clamped Beams," Jour. App. Mechs., Vol. 32, No. 1, 1965, pp. 7-10.

(10) Bodner, S. R., and Symonds, P. S., "Experimental and Theoretical Investigation of the Plastic Deformation of Cantilever Beams Subjected to Impulsive Loading," J. App. Mechs., Vol. 29, No. 4, 1962 pp. 719-728.

(11) Jones, N., "The Influence of Strain-Hardening and Strain--Rate Sensitivity on the Permanent Deformation of Impulsively Loaded Rigid-Plastic Beams." Int. Jour. Mech. Sci., Vol. 9, No. 12, pp. 777-796, 1967.

(12) Jones, N., "Finite Deflections of a Rigid-Viscoplastic

Strain-Hardening Annular Plate Loaded Impulsively," J. App. Mechs., Vol. 35, No. 2, pp. 349-356, 1968.

(13) Jones, N., Griffin, R. R., and Van Duzer, R. E., "An Experimental Study into the Dynamic Plastic Behavior of Wide Beams and Rectangular Plates," Mass. Inst. of Tech., Dept. of Nav. Arch. and Mar. Engr. Report No. 69-12, 1969.

(14) Jones, N., Uran, T. O., Tekin, S. A., "The Dynamic Plastic Behavior of Fully Clamped Rectangular Plates," Mass. Inst. of Tech. Dept. of Nav. Arch. and Mar. Engr., Report No. 69-13, 1969.

(15) Florence, A. L., "Buckling of Viscoplastic Cylindrical Shells due to Impulsive Loading," AIAA Journal Vol. 6, No. 3, March 1968.

(16) Clark, E. N., Schmitt, F. H., and Juriaco, I. P., "Plastic Deformation of Structures, Part III, Large Plastic Deformation of Clamped Cylindrical Panels," AFFDL-TDR 64-64 Vol. III, Engineering Sci. Lab, Picatinny Arsenal, Dover, N. J., 1968.

(17) Leech, J. W., Witmer, E. A., and Pian, T. H. H., "A Numerical Calculation Technique For Large Elastic-Plastic Transient Deformations of Thin Shells," A. I. A. A. Journal, Vol. 6, No. 12, pp. 2352-2359, 1968.

(18) Clark, E. N., Schmitt, F. H., Ellington, D. G., Engle, I. A., and Nicolaides, S., "Plastic Deformation of Structures: Volume I - Plastic Deformation Beams." Air Force Flight Dynamics Laboratory. FDL-TDR-64-64, May 1965.

(19) Daily, J. W., and Harleman, D. R. F., "Fluid Dynamics" Addison-Wesley Publishing Co., Inc., Reading, Mass. 1966